



# CHICAGO AIR POLLUTION SYSTEM MODEL

**ARGONNE NATIONAL LABORATORY**

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City of Chicago

Air Pollution System Model

ARGONNE NATIONAL LABORATORY  
CHICAGO DEPARTMENT OF AIR POLLUTION CONTROL  
DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE  
National Center for Air Pollution Control

Third Quarterly Progress Report

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by

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ENVIRONMENTAL SCIENCES



### FOREWORD

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TABLE OF CONTENTS

	<u>Page</u>
1.0 Introduction . . . . .	16
2.0 Dispersion Analysis. . . . .	20
2.1 Discussion . . . . .	20
2.2 Temperature Dependent Sources. . . . .	22
2.3 Correlation of TAM Station SO <sub>2</sub> Measurements with Temperature Dependent Sources. . . . .	26
2.3.1 Quadrant Survey. . . . .	26
2.3.2 Emission Data for the Quadrant Survey. . . . .	31
2.3.3 SO <sub>2</sub> Levels Correlated with Residential and Commercial Emissions. . . . .	33
2.4 Development and Validation of Prediction Algorithms. . . . .	39
2.4.1 Octant Survey. . . . .	39
2.4.2 Regression Analysis Results. . . . .	46
2.4.3 Conclusions. . . . .	48
2.5 Pollution Incident Frequency Survey. . . . .	50
2.6 Plume Studies. . . . .	65
2.6.1 Major Point Sources. . . . .	65
2.6.2 Nonlinear Coupling with Close-in Stacks. . . . .	71
2.7 Discriminant Analysis Evaluation Tests . . . . .	73
2.7.1 Partitioning the Data. . . . .	73
2.7.2 Discriminant Analysis Test Results . . . . .	75
2.7.3 Validation . . . . .	87

TABLE OF CONTENTS (Contd.)

	<u>Page</u>
3.0 Meteorology . . . . .	94
3.1 Meteorological Data Acquisition . . . . .	94
3.2 Experimental Studies. . . . .	94
3.2.1 Instrumenting Buildings . . . . .	94
3.2.2 Helicopter Program. . . . .	95
3.2.3 Tracer Studies. . . . .	96
3.2.4 Second Air Pollution Control Test . . . . .	99
3.3 Analytical Meteorology. . . . .	109
3.3.1 SO <sub>2</sub> Regression Upon Temperature: Meteorological Analysis of Anomalous Data Points . . . . .	111
3.3.2 Wind Direction Differences in Chicago . . . . .	117
3.3.3 The Episode of 19-20 January 1966 . . . . .	129
3.3.4 Identification of Air Pollution Incidents: Preliminary Results . . . . .	146
3.3.5 Conclusions . . . . .	148
4.0 Emission Inventory. . . . .	152
4.1 Field Emission Survey . . . . .	152
4.2 Stoker Monitors . . . . .	153
4.3 Coal Utilization in Chicago . . . . .	155
5.0 Applied Programming . . . . .	164
6.0 Abatement Strategy and Economics. . . . .	168
6.1 Relationship of Prediction and Control Models . . . . .	168
6.2 Types of Control. . . . .	169

TABLE OF CONTENTS (Contd.)

	<u>Page</u>
6.3 Incident Control . . . . .	171
6.3.1 Advantages of Incident Control . . . . .	171
6.3.2 Difficulties of Incident Control . . . . .	172
6.4 Commonwealth Edison Company Pilot Study. . . . .	173
6.4.1 The Pilot Study Control Subsystem. . . . .	174
6.4.2 Physical Characteristics of the Power Generation System. . . .	174
6.4.3 Feasibility of Control . . . . .	185
6.4.4 Formulation of the Mathematical Control Model. . . . .	189
6.4.5 Solution of the Mathematical Control Model via Linear Programming . . . . .	197
6.4.6 Discussion of Results and Model Validity . . . . .	204
6.4.7 Extensions of the Optimal Control Model. . . . .	217
6.5 Economic Studies . . . . .	219
6.5.1 General Discussion . . . . .	219
6.5.2 Power Plant SO <sub>2</sub> Abatement. . . . .	220
6.5.3 Industry SO <sub>2</sub> Emission Abatement. . . . .	225
7.0 Air Pollution Operations Manual. . . . .	238
7.1 Air Pollution Abatement Planning . . . . .	240
7.2 Air Pollution Prediction . . . . .	241
7.3 Progress Achieved to Date. . . . .	247
7.4 Conclusions. . . . .	249
ACKNOWLEDGEMENTS. . . . .	251
REFERENCES. . . . .	252

LIST OF FIGURES

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
2.1	Proposed Janitor Function	25
2.2	Pollution Incident Control Plan Map	28
2.3	Quadrant Survey - $\text{SO}_2$ Levels vs. Residential (1-19 DU/Bldg) and Commercial Emissions. January - February - March 1967. WS = 5.5 - 9.5 mph. Heating Hours. Stability Class 4	34
2.4	Quadrant Survey - $\text{SO}_2$ Levels vs. Residential ( <u>All Buildings</u> ) and Commercial Emissions. January - February - March 1967. WS = 5.5 - 9.5 mph. Heating Hours. Stability Class 4	36
2.5	Regression Lines for TAM 4. January - February - March 1967. Stability Class 4. No Precipitation	41
2.6	Regression Lines for TAM 4. January - February - March 1967. Stability Class 4. No Precipitation	42
2.7	TAM 4 Averages $\text{SO}_2$ Values for Three Degree Temperature Bands. Stability Class 4. Numbers Indicate Number of Hours Data Points Averaged Together	43
2.8	Average $\text{SO}_2$ Values for Three Degree Temperature Bands. Stability Class 4. Numbers Indicate Number of Hourly Data Points Averaged Together	44
2.9	Prediction of January - February 1968 - $\text{SO}_2$ Levels by Algorithms Derived from 1967 Data	47
2.10	Non-Linear Effect of Plume Rise. Based on a U.C. Stack (200 ft High with Maximum Output of 6 M cal/sec). Stability Class 4	72
3.1	Schematic Diagram of Chromatographic System for $\text{SF}_6$ Analysis	98
3.2	Time Section of $\text{SO}_2$ Concentrations and Wind Velocities at Selected TAM Stations, Rural (Argonne) Lapse Rate, Stability Index and Period of Precipitation, 1 July 1968	104

LIST OF FIGURES (contd).

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
3.3	Time Section of $SO_2$ Concentrations and Wind Velocities at Selected TAM Stations, Rural (Argonne) Lapse Rate, Stability Index, 3 July 1968	106
3.4	Frequency Distribution of Deviations from Temperature Regression Lines	113
3.5	Distribution of High and Low Days by Day of the Week	114
3.6	Distribution of High and Low Hours by Hour of the Day	116
3.7	Distribution of Wind Direction at O'Hare for Specified Midway Winds	118
3.8	Distribution of Wind Direction at Glenview for Specified Midway Winds	119
3.9	Distribution of Wind Direction at Argonne for Specified Midway Winds	121
3.10a	Distribution of Wind Direction at TAM 6 for Specified Midway Winds	122
3.10b	Distribution of Wind Direction at TAM 6 for Specified Midway Winds	123
3.11a	Distribution of Wind Direction at TAM 7 for Specified Midway Winds	124
3.11b	Distribution of Wind Direction at TAM 7 for Specified Midway Winds	125
3.12a	Distribution of Wind Direction at Midway for Specified TAM 4 Winds	127
3.12b	Distribution of Wind Direction at Midway for Specified TAM 4 Winds	128
3.13	Time Series of TAM 4 $SO_2$ and Winds, Plus Midway Temperature, 16-21 January 1966	130
3.14	Time Series of TAM 5 $SO_2$ and Winds, Plus Midway Temperature, 16-21 January 1966	131

LIST OF FIGURES (contd).

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
3.15a	Surface Weather Maps for 15-21 January 1966 (1200 CST)	133
3.15b	Surface Weather Maps for 15-21 January 1966 (1200 CST)	134
3.16	Time Series of SO <sub>2</sub> and Winds for TAM 2, 3, 4, 5 and 6. 19 January 1966	136
3.17a	Wind Field over Chicago on 19 January 1966	137
3.17b	Wind Field over Chicago on 19 January 1966	138
3.18	Schematic Diagram of a City-Rural Circulation (After Lowry, 1967)	140
3.19	Temperature Variations at Midway, O'Hare and Argonne, 19 January 1966	142
3.20	Winds Aloft at Green Bay and Peoria on 19-20 January 1966	143
3.21	Time Series of Hourly Average SO <sub>2</sub> > 0.20 ppm for Chicago TAM Stations, January 1966	147
4.1	Chicago Coal Consumption 1,000,000 Tons Burned	158
4.2	Chicago Yearly SO <sub>2</sub> Emissions Projected to 1980	159
4.3	Chicago Average Yearly SO <sub>2</sub> Emissions - to 1967	160
4.4	TAM 3 Oriented Source Map	161
6.1	Power Plant Pilot Study System	175
6.2	Power Company Network	177
6.3	Typical Winter Daily Load Pattern	179
6.4	Utility Power Generation Control System	180
6.5	Typical Gross Thermal Input vs. Load Curve and Least Squares Approximating Line	198

LIST OF FIGURES (contd).

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
6.6	Graphical Solution of a Linear Programming Problem	200
6.7	Teleprocessing Control System Schematic	205
6.8	Predicted and Measured Air Quality at Lindbloom Receptor During Test Incident	206
6.9	Surface Weather Map, 1200 CST, 31 January 1966	208
6.10	Atmospheric Temperature Soundings, Showing Construction of Chicago Rural Sounding and Estimation of Chicago Mixing Depth	210
6.11	Hourly SO <sub>2</sub> Levels at Lindbloom Receptor for WS = 2 mph	213
6.12	Hourly SO <sub>2</sub> Levels at Hyde Park for WS = 2 mph	214
6.13	Hourly SO <sub>2</sub> Levels at Lindbloom for WS = 4 mph	215

LIST OF TABLES

<u>Number</u>	<u>Title</u>	<u>Page</u>
2.1	University of Chicago Hourly Fuel Use Correlations	23
2.2	Quadrant Survey of Temperature Dependence WS = 5.5 - 9.5 mph - Neutral Stability (Class 4)	29
2.3	Annual SO <sub>2</sub> Emissions from Residential and Commercial Sources Associated with the Quadrant Survey	32
2.4	1 Hour SO <sub>2</sub> Concentrations	53
2.5	6 Hour SO <sub>2</sub> Concentrations	54
2.6	12 Hour SO <sub>2</sub> Concentrations	55
2.7	18 Hour SO <sub>2</sub> Concentrations	56
2.8	Total Number of One Hour SO <sub>2</sub> Incidents (1966-67)	57
2.9	Total Number of Six Hour SO <sub>2</sub> Incidents (1966-67)	57
2.10	Total Number of 12 Hour SO <sub>2</sub> Incidents (1966-67)	58
2.11	Total Number of 18 Hour SO <sub>2</sub> Incidents (1966-67)	58
2.12	Point Source Contributions to TAM Stations Directly Downwind [WS = 10 mph]	67
2.13	Dispersion Parameters. Approximations to Curves by Turner <sup>3</sup>	68
2.14	Discriminant Analysis Hyde Park TAM Station Winter 1966-67	76
2.15	Discriminant Analysis Hyde Park TAM Station Spring 1966-67	77
2.16	Discriminant Analysis Hyde Park TAM Station Summer 1966-67	78
2.17	Discriminant Analysis Hyde Park TAM Station Fall 1966-67	79

LIST OF TABLES (contd).

<u>Number</u>	<u>Title</u>	<u>Page</u>
2.18	Discriminant Analysis Hyde Park TAM Station Fall - Winter - Spring 1966-67	80
2.19	Discriminant Analysis Lakeview TAM Station Summer 1966-67	88
4.1	Tonnage Delivered in 1966 - Tons of SO <sub>2</sub> - % Sulfur - Chicago Area and within One Mile of Corporate Limit	156
4.2	Tonnage and SO <sub>2</sub> Projections - Chicago Plus Area within One Mile of Corporate Limit	157
6.1	Optimal Emission Control Strategy - Typical Computer Output	202
6.2	Optimal Emission Control Strategy - Typical Computer Output	203
6.3	Estimated Chicago Mixing Depths, 1 February 1966	209



# CHICAGO AIR POLLUTION DISPERSION MODEL

## 1.0 Introduction

E. Croke

1.0 Introduction

The first and second quarters of the Chicago Air Pollution System Analysis Program included a survey of the state-of-the-art of atmospheric dispersion analysis, the definition and scoping of tasks associated with the construction of a computerized  $\text{SO}_2$  dispersion model, the initiation of the necessary data acquisition effort and the development of computational tools and analytical methods required to process, store, retrieve and analyze the available inventory of emission, meteorology and air quality data. Preliminary analytical studies of Chicago air pollution meteorology and  $\text{SO}_2$  dispersion were undertaken, and an experimental program designed to provide the necessary support for further investigations was formulated. Details of the progress achieved during this period are reported in the first and second quarterly progress reports (ANL/ES-CC-001 and -002).

During the second quarter of the Chicago Air Pollution System Analysis program, the development of the air pollution master information system was completed and a large inventory of emission, meteorological and air quality data was stored in the master data file.

In the third quarter of the program, it was therefore possible to initiate a comprehensive series of analytical studies of local air pollution meteorology and  $\text{SO}_2$  dispersion characteristics, to formulate and validate tentative,  $\text{SO}_2$  "prediction" algorithms and to conduct in-depth meteorological case studies of Chicago air pollution episodes, utilizing the data retrieval, sorting, processing and analytical capabilities

provided by the master information system. Preliminary tests of multivariate discriminant analysis were conducted in order to evaluate the effectiveness of this technique as an analytical tool, and the development of an urban mixing layer depth computational algorithm was initiated.

The experimental program remains largely in its preparatory stages as yet; however, shakedown trials of the modified gas chromatograph to be employed in the sulfur hexafluoride tracer studies were implemented during this period, and preparations for the helicopter sounding studies and building instrumentation program were advanced. A second  $\text{SO}_2$  incident control exercise was planned and executed during this period, and an analysis of its effectiveness was initiated.

One of the more significant program milestones that was achieved during the third quarter was the completion of the optimal, incident abatement pilot study, which was conducted with the cooperation of the Commonwealth Edison Company. A computerized, incident control strategy, based on a source-oriented dispersion model and a standard linear programming algorithm, was developed for key stations in the urban power plant network. This strategy automatically generates a minimum cost  $\text{SO}_2$  incident abatement plan within the physical, economic and operational constraints normally imposed on the Edison system.

A preliminary cost-effectiveness study of a city-wide  $\text{SO}_2$  incident abatement strategy, based on total  $\text{SO}_2$  emission control, was also completed. The results of this study represent the first attempt to evaluate the economic impact of an incident control operation in Chicago.

Details of these studies and other investigations conducted in support of the Chicago Air Pollution System Analysis Program are discussed in the following sections of this report.

# CHICAGO AIR POLLUTION DISPERSION MODEL

## 2.0 Diffusion Analysis

J. Roberts  
E. Croke

## 2.0 Dispersion Analysis

### 2.1 Discussion

The master data file is now operational with two years of meteorological information,  $\text{SO}_2$  concentrations, and emission profiles for key point sources, including the major CECO plants. The complete dispersion model described in earlier reports<sup>(1,2)</sup> is therefore ready for evaluation. Proposed in the form of a linear regression equation,

$$X_n = C_0 + C_1 P_1(T_n) + C_2 P_2(T_n) + \sum_{i=1}^I K_i Q_{in}, \quad n = 1, \dots, N \quad (1)$$

the model is described in terms of the magnitudes and statistical significance of the background ( $C_0$ ), temperature dependent patterns ( $C_1, C_2$ ), and point source coupling coefficients ( $K_i$ ,  $i = 1, I$ ) which are to be determined by correlation with up to two years of historical hourly data.

To a certain extent, the problem presented by this data inventory involves a trial and error, or adaptive, analytical effort. This is particularly evident in view of the fact that the data must be divided into subsets characterized by similar dispersion properties. That is, "met sets"<sup>(2)</sup> must be established which partition the data into consistent meteorological regimes, yet which are sufficiently broad to include enough data points to yield good statistical correlation.

Furthermore, the modeling effort is incomplete if regression coefficients (in particular those for heating patterns  $P_1$  and  $P_2$ ) are estimated for each TAM station without a subsequent attempt to interrelate the coefficients in terms of known sources. For example, stack coupling

coefficients might be intercorrelated in terms of  $\sigma_y$  and  $\sigma_z$  functions for a standard plume equation. Similarly, the relative importance of heating patterns at different TAM stations must be interrelated by correlation with existing residential and commercial densities.

This third report on the dispersion model development describes the preliminary effort to establish met sets and evaluate the relative importance of various source classifications. In particular, the sensitivity of  $SO_2$  levels to temperature was evaluated by a city wide survey considering four wind direction quadrants at each of the eight TAM stations. A modified janitor function<sup>(2)</sup> is employed in both the city wide quadrant survey, and a detailed examination of Hyde Park (TAM 4) data. The effort in this area has been focused on "normal" meteorological conditions for Chicago, which are characterized by a neutral or slightly unstable atmosphere. The study of pollution incidents, including nocturnal inversions of short duration, prolonged periods of stagnation, etc., is being conducted as a parallel effort described elsewhere in this report.

Statistical coupling coefficients for point sources, in particular the power plants, have not yet been evaluated. This section discusses some theoretical predictions which lend weight to the proposition that, for normal meteorological conditions in Chicago, these plants will be difficult to detect against the general  $SO_2$  background. However, it is also likely that these plants contribute significant amounts of  $SO_2$  at ground level during pollution incidents.

## 2.2 Temperature Dependent Sources

Residential, commercial, and a significant percentage of industrial fuel requirements represent temperature dependent emissions of sulfur dioxide. Correlations of fuel use data with Midway Airport daily and hourly temperature averages support the generally accepted and physically reasonable assumption of a linear relationship between heating degrees and fuel requirements. This linearity exists above a base level of fuel consumption for water heating and other services which are relatively independent of temperature.

The emission inventory data acquisition and analysis studies which were presented in the second quarterly progress report indicated strong and somewhat uniform correlation between daily fuel use and heating degree days for several high pressure steam systems (U.C., IIT, and Stateway Apartments). Considering the similarity of regression coefficients for daily fuel requirements, it is reasonable to assume that these high pressure steam plants can be represented on an hourly basis by the hourly fuel consumption rates for the University of Chicago. Results in Table 2.1 are representative of many regressions based on a linear relationship between fuel consumption and Midway Airport temperature. These show that the University heating plant is well characterized by the same temperature dependence for all hours of day and night.

Table 2.1 University of Chicago Hourly Fuel Use Correlations

$$Q = C_o + C_1 [\text{Midway Hourly Temperature}]$$

Data Set	# Points	$C_o$	$C_1$	R
Jan. '66, Dec. '66, Jan. '67 Hours 10-15 Cloud Cover $\leq 0.8$	241	20	-.18	.90
Same Months Hours 1-24 Cloud Cover $\leq .9$	1088	19	-.18	.85

No useful experimental data is available as yet for low pressure steam plants. Stoker monitors installed last spring yielded insufficient information (about two weeks of data over a very limited temperature range). Although it seems reasonable to assume a linear relationship between fuel consumption and heating degrees, there is evidence (to be discussed later) that a much sharper temperature dependence exists below freezing than above. This effect will be evaluated in future work. For the studies described here, the temperature pattern was assumed to be linear below a 55°F base. This latter figure was derived on the basis of a series of interviews with building superintendents in the Hyde Park area who tended to agree that a hold fire interval of 6 minutes stoking/hour is realistic for temperatures above 55°F.

In the following discussion, high pressure, 24 hour steam plants are represented by a heating degree pattern with a 55°F base:

$$P_1(T_n) = 55^\circ\text{F} - T_n \quad (2)$$

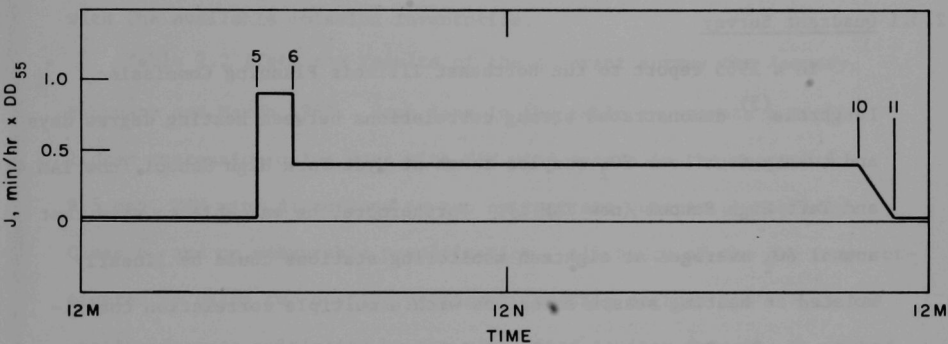
The low pressure plants follow the same relationship but modified by the "janitor function."<sup>(1,2)</sup>

The janitor function, which reflects the fact that, independent of temperature, low pressure steam plants are cut back to a hold fire between the hours of 2300 or 2400 and 0600, has been proposed in the form shown in Figure 2.1.

The existence of a high emission early morning burn period corresponding to increased stoking during this heat-up interval would seem to be substantiated by the frequently observed early morning buildup of  $\text{SO}_2$ . However, a survey of a dense residential area (Hyde Park) for over fifty hours in this category clearly indicates two facts:

- 1) When the Turner stability index<sup>(3)</sup> has a value of 4, corresponding to a neutral or slightly unstable atmosphere, (Brookhaven Class B1)<sup>(4)</sup> the early morning  $\text{SO}_2$  levels after 6 AM obey the daytime temperature dependence and exhibit no peak;
- 2) Almost every early morning peak is associated with a stable (Class 5) atmosphere.

It therefore appears that meteorological effects alone account for early morning  $\text{SO}_2$  peaks, even in dense residential areas. The janitor function originally proposed has therefore been simplified and is now represented by a unit step function between the hours of 0600 and 2300. One can rightly ask how it is possible to justify such a modification of the janitor function if this function is to represent an actual stoker pattern which is known to peak when thermostatic control is first



112-7214

Fig. 2.1 Proposed Janitor Function

activated each day. The rationale is that this function is not strictly representative of the stoker pattern alone, but of the stoker pattern modified by such variables as transport lags. Differences in the times at which boilers are fired up, combined with transport lags and the fact that it takes time for the ambient  $\text{SO}_2$  level to increase from the nocturnal background level to the level associated with the outside temperature adequately accounts for the smoothing of what would probably otherwise be an early morning peak in  $\text{SO}_2$  attributable solely to a residential heating pattern.

### 2.3 Correlation of TAM Station $\text{SO}_2$ Measurements with Temperature Dependent Sources

#### 2.3.1 Quadrant Survey

In a 1965 report to the Northeast Illinois Planning Commission, Longbrake<sup>(5)</sup> demonstrated strong correlations between heating degree days and twenty-four hour  $\text{SO}_2$  samples taken at Hyde Park High School (now TAM 4) and Taft High School (now TAM 1). Furthermore, he was able to show that annual  $\text{SO}_2$  averages at eighteen monitoring stations could be linearly related to heating season emissions with a multiple correlation coefficient of .9. Recently, a study of fifteen months of 6 hour  $\text{SO}_2$  averages for Reading, England<sup>(6)</sup> emphasized the poor correlation of  $\text{SO}_2$  concentrations with industrial stacks and the close relationship to residential density. It therefore seems reasonable to pursue this argument and survey Chicago by testing, on an hourly basis, for temperature dependence associated with different wind directions at each of the eight TAM stations and comparing the results to known residential and commercial emissions.

Residential and commercial fuel use has been inventoried by both the city of Chicago (DAPC) and Peoples Gas Light and Coke Company (PGLC) on a square mile basis. This quantification, coupled with the assumption that low lying sources within a mile of the TAM receptors dominate the air quality measurements means that reasonable wind direction bands could be resolved to no better than about  $90^\circ$ . As indicated by the map, (Fig. 2.2) many of the TAM stations are sited on major crossroads which coincide with the intersections on the official square mile grid used in both DAPC and PGLC inventories. A finer azimuthal breakdown which would be sensitive to inhomogeneities within each square mile is not possible with the available emission inventories.

Table 2.2 lists the results of the quadrant survey for January, February and March 1967. Each line in the table represents a single linear regression using data with TAM wind speeds in the range 5.5 - 9.5 mph, TAM wind directions in the appropriate quadrant, stability Class 4, and no measurable precipitation. All hours of the day were considered by using two heating patterns: heating degrees ( $55^\circ\text{F} - T$ ) and heating degrees multiplied by the simplified janitor function discussed in Section 2.1. This survey was designed to permit assessment not only of temperature dependence but also of the relative importance of high and low pressure steam heating systems.

An examination of Table 2.2 - in particular the right hand column which lists multiple correlation coefficients - indicates that direct temperature correlations are relatively weak in the majority of cases.

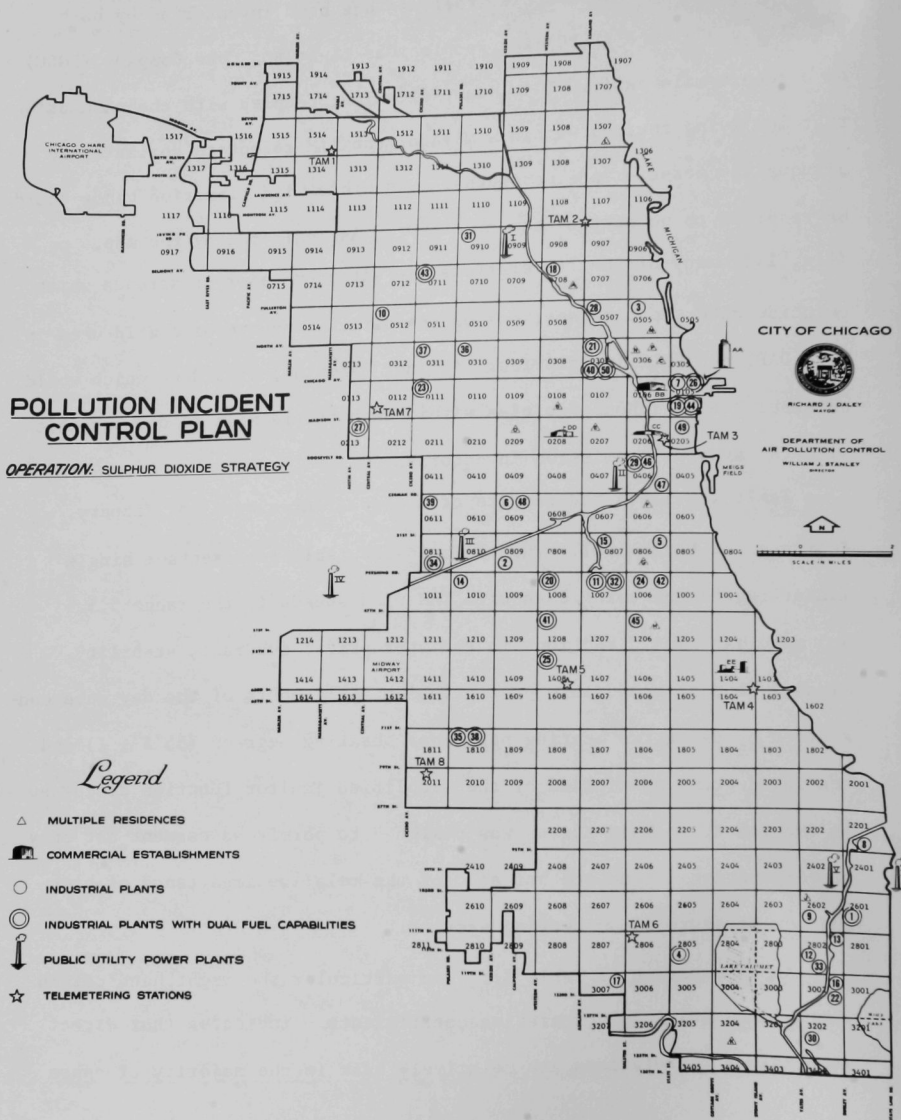


Fig. 2.2 Pollution Incident Control Plan Map

Table 2.2 Quadrant Survey of Temperature Dependence WS = 5.5 - 9.5 mph  
Neutral Stability (Class 4)

TAM	WD	TEMP Range (°F)	# DATA POINTS	Regression Coefficients <sup>a</sup>				R
				C <sub>0</sub>	C <sub>1</sub> × 10 <sup>3</sup> (ppm 1°F)	C <sub>2</sub> × 10 <sup>3</sup> (ppm)	σ	
1	NE	28 ± 8	55	-.01	1.0	1.2	.05	.33
	SE	28 ± 6	49	-.09	8.6	-.3	.09	.50
	SW	28 ± 10	138	.02	1.1	.3	.06	.24
	NW	18 ± 11	92	.02	.3	.2	.01	.28
2	NE	30 ± 8	40	.06	0	2.0	.03	.65
	SE	30 ± 7	28	.19	-2.5	1.6	.09	.17
	SW	31 ± 12	52	.17	.2	3.3	.11	.37
	NW	22 ± 13		.06	.3	.9	.04	.49
3	NE	30 ± 8	47	.10	2.9	2.1	.05	.66
	SE	28 ± 4	37	.31	1.6	-1.9	.12	.19
	SW	29 ± 10	132	.27	1.3	1.8	.13	.26
	NW	21 ± 12	125	.23	3.8	1.7	.11	.49
4	NE	31 ± 7	55	.01	1.4	1.0	.04	.34
	SE	26 ± 7	29	-.14	7.7	3.6	.12	.60
	SW	28 ± 9	182	.13	-.7	4.1	.07	.60
	NW	15 ± 10	73	.18	.6	2.7	.11	.45
5	NE	30 ± 6	72	.01	1.1	1.9	.05	.42
	SE	25 ± 8	49	.01	1.2	.8	.04	.44
	SW	29 ± 11	76	.04	.4	.7	.03	.38
	NW	22 ± 12	79	.14	-1.4	.7	.06	.31
6	NE							
	SE	26 ± 7	49	.01	.2	.6	.03	.30
	SW	29 ± 10	157	.03	0	.5	.03	.23
	NW		151	.03	.4	.5	.04	.26
7	NE	27 ± 12	42	.27	-6.1	5.4	.14	.38
	SE	29 ± 10	183	.10	-.7	2.3	.10	.27
	SW	21 ± 12	129	.05	-.5	1.1	.05	.37
	NW	31 ± 8	46	.14	-3.0	.8	.05	.41
8	NE	31 ± 7	48	.08	-1.2	1.4	.05	.31
	SE	24 ± 11	40	.05	0	.6	.03	.27
	SW	29 ± 11	87	.06	-.3	.4	.03	.12
	NW	22 ± 12	86	.07	-.6	1.0	.07	.23

a) Regression Coefficients based on:

$$X_n = C_0 + C_1(55^\circ\text{F} - T_n) + C_2(55^\circ\text{F} - T_n)(\text{Janitor Fct.})$$

Janitor Function = 1 hours 6-23

0 hours 24 and 1-5

In only about one in four examples does the regression line explain as much as 25% of the variance in the original data. Nevertheless, the standard deviations tabulated in the adjacent column are low when one considers that  $\text{SO}_2$  values within some of these data sets range from .01 to greater than .4 ppm, depending upon location and temperature. It appears that outlying sources such as Cicero and Gary and distributed industry in general are responsible for a background or  $\text{SO}_2$  "noise level" throughout the city at the level of .02 - .05 ppm  $\text{SO}_2$ , and that only areas of strong residential or commercial source strength significantly penetrate this level with significant temperature dependent emission signals. This effect is more evident in Section 2.3.3 where  $\text{SO}_2$  levels are shown against plotted residential and commercial emissions.

Wind speed and direction for each of the 32 runs described here were based on TAM station values as opposed to Midway Airport data (see Section 3.0 for a discussion of this decision). Because of discrepancies between aerovane readings - some due to actual variations in the wind field and others due to building interference - and because of missing  $\text{SO}_2$  or aerovane data, the numbers of data points for winds in each quadrant are not consistent from station to station. A prime example of this effect is shown for winds from the SW quadrant for which TAM stations 1, 3, 4, 6 and 7 list over 130 hourly values while stations 2, 5 and 8, respectively, list 52, 76 and 87 data points. Considering the large wind direction band that was surveyed, it would seem that wind velocity is the key parameter responsible for this selectivity phenomenon, since it is

restricted to a comparatively narrower range and is quite sensitive to building interference. Unusual effects such as this must be studied in detail - at best a tedious process. Our present intentions are to rerun this quadrant survey using Midway wind parameters in the met set modified by special checks for phenomena such as lake breezes, which produce significant variations in the wind field over Chicago.

### 2.3.2 Emission Data for the Quadrant Survey

The most recent detailed survey of residential and commercial heating densities in Chicago is the 1964 DAPC emission inventory. This, in turn, was based on the 1961 city wide survey by the Rates and Markets Department of PGLC.

Data for an up-to-date survey similar to the 1961 effort was recently acquired by PGLC. Approximately 20% of this information has been processed, and a special tabulation giving separate estimates of oil and coal consumption for various classes of buildings on a mile square basis about each TAM station (Table 2.3) was prepared for Argonne. The PGLC inventory is a sampling of approximately 9% of the buildings in the 1-7 DU/building<sup>\*</sup> class and 17% of those in the 8-19 class. All buildings over 4 stories are evaluated. Twenty percent of this data is in the preliminary tabulation prepared for Argonne and has been converted, using DAPC emission factors,<sup>(7)</sup> to annual SO<sub>2</sub> output. The data is listed in Table 2.3. This information will be updated in coming months as a greater percentage of the PGLC 1967 survey is processed.

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\* dwelling units

TABLE 2.3 Annual SO<sub>2</sub> Emissions from Residential and CommercialSources Associated with the Quadrant Survey  
(million pounds SO<sub>2</sub>/mi<sup>2</sup>)

TAM	WD	1-7 DU/Bldg. <sup>a,c</sup>	8-19 DU/Bldg. <sup>a,d</sup>	>20 DU/Bldg. <sup>a,d</sup>	Commercial <sup>b</sup>	1964 Total Res. + Com'l (Ref. 4) <sup>b</sup>
1	NE	.06	0	0	.14	.4
	SE	.04	0	0	.16	.5
	SW	.03	0	0	.07	.3
	NW	.01	0	0	.19	.4
2	NE	.8	1.3	3.3	.5	4.1
	SE	.5	.5	1.1	.7	2.8
	SW	.3	.3	.1	.5	1.8
	NW	.2	.4	.8	.6	2.2
3	NE	0	0	0	2.8	2.8
	SE	0	0	.1	1.7	1.9
	SW	.01	0	0	1.0	1.2
	NW	0	0	0	3.2	3.2
4	NE	0	.1	.2	.1	.4
	SE	.8	.2	1.3	.2	.9
	SW	.3	1.9	1.2	.4	2.7
	NW	.6	.9	1.4	1.1	2.3
5	NE	.7	.3	.1	.3	2.0
	SE	.9	.3	.1	.3	2.0
	SW	.3	.1	0	.3	1.2
	NW	.1	.1	0	.4	1.1
6	NE	.1	.1	0	.1	.5
	SE	.2	.1	0	.1	.8
	SW	.02	0	0	.2	.3
	NW	.1	0	0	.2	.5
7	NE	.5	.3	.9	.4	1.7
	SE	.2	.2	.5	.4	1.2
	SW	.1	.2	.1	.7	1.1
	NW	.04	.1	.7	.3	2.8
8	Inadequate data but emissions are very low.					

a) Based on partial reduction of 1967 PGLC survey.

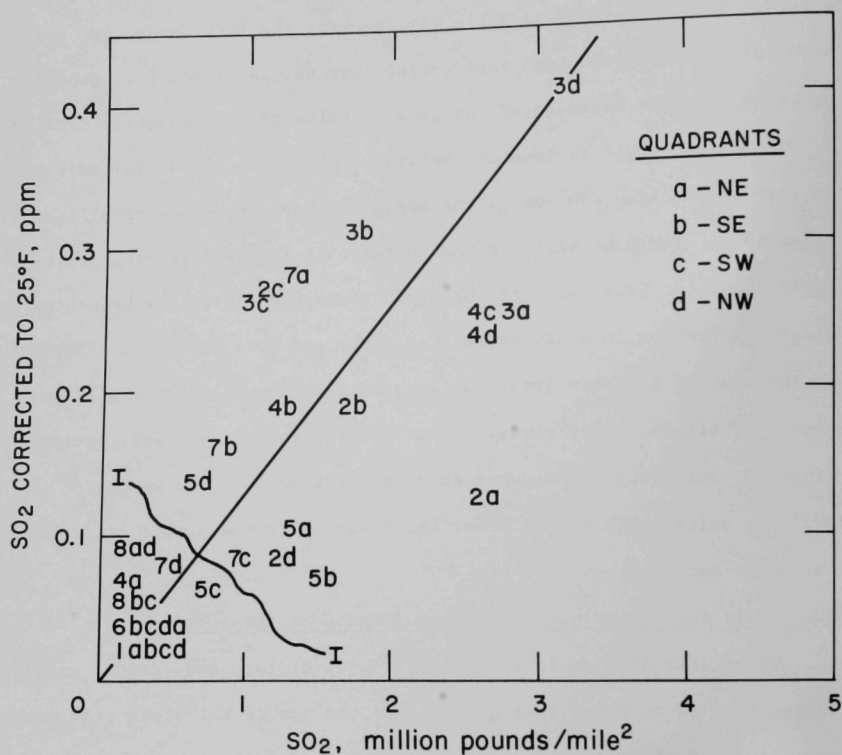
b) Based on 1964 DAPC emission inventory.

c) Assumes 100 lb SO<sub>2</sub> (500 lb SO<sub>2</sub>) per DU per year for light oil (coal) buildings.d) Assumes 150 lb SO<sub>2</sub> (300 lb SO<sub>2</sub>) per DU per year for heavy oil (coal) buildings.

Preliminary estimates by PGLC of the 1967 fuel requirements of commercial fuel users are also available, but at the time of this report, these have not been converted to annual  $\text{SO}_2$  emissions. For this category, therefore, data listed in Table 2.3 is based on the 1964 DAPC survey. The final entry in Table 2.3, showing the 1964 annual  $\text{SO}_2$  emission for all commercial and residential sources, is listed for comparison with the best estimate of the present value of this quantity obtained by summing 1967 PGLC residential estimates with 1964 commercial emissions. In five of 28 cases,  $\text{SO}_2$  emissions appear to have increased significantly since 1964. TAM 2 NE reflects the increase in luxury high rise apartments along the Lake north of Chicago. Similarly, there has been high rise construction in South Shore (TAM 4 SE) and Hyde Park (TAM 4 NE) but another factor in these areas may be a better accounting of the large number of illegal conversions. This latter point affects fuel estimates since  $\text{SO}_2$  emissions are assumed to be proportional to the number of dwelling units, with second order corrections for the number of dwelling units per building.

### 2.3.3 $\text{SO}_2$ Levels Correlated with Residential and Commercial Emissions

The sulfur dioxide level characteristic of each quadrant at each TAM station is compared in Figure 2.3 to the sum of emissions from residential (1-19 DU/Unit) and commercial sources for the appropriate square mile. Where the temperature relationship is significant, the  $\text{SO}_2$  value has been corrected to 25°F using the regression coefficients of Table 2.2. Standard deviations of up to  $\pm 1$  ppm are associated with the data points.



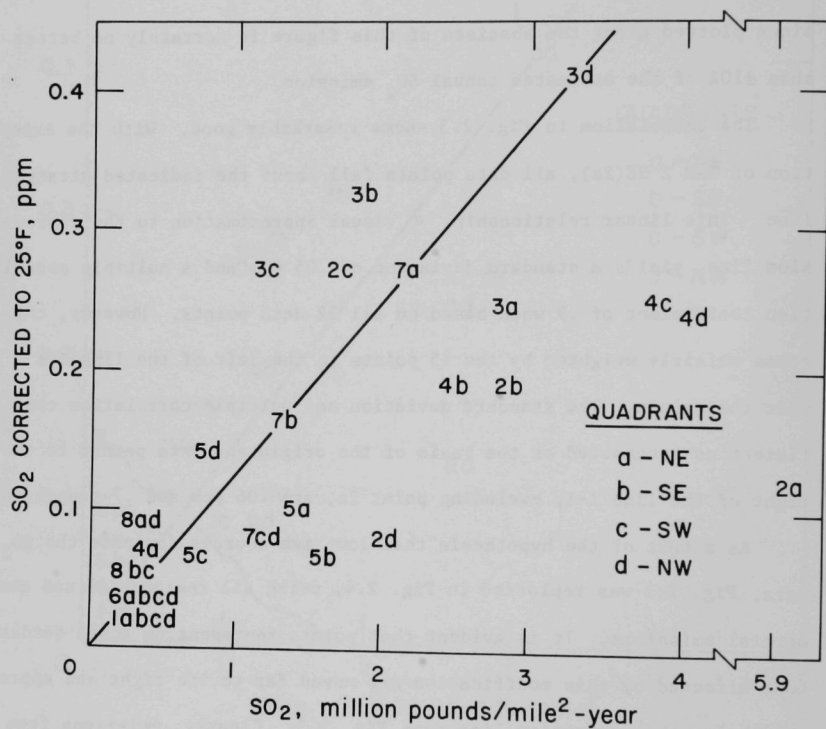
112-9755

Fig. 2.3 Quadrant Survey-SO<sub>2</sub> Levels vs. Residential (1-19 Du/Bldg) and Commercial Emissions: Jan.-Feb.-March 1967. Ws = 5.5-9.5 mph Heating Hours. Stability Class 4

Residential units in both the 1-7 DU/building and 8-19 DU/building categories were chosen for the abscissa of this plot on the assumption that low-rise (1-4 story) sources were mainly responsible for ground level  $\text{SO}_2$ . Older Chicago buildings up to the 19 DU/building class are typically court-type, three or four story structures. The accuracy of emissions plotted along the abscissa of this figure is certainly no better than  $\pm 10\%$  of the estimated annual  $\text{SO}_2$  emission.

The correlation in Fig. 2.3 seems remarkably good. With the exception of TAM 2 NE(2a), all data points fall about the indicated straight line. This linear relationship, a visual approximation to the regression line, yields a standard deviation of .05 ppm and a multiple correlation coefficient of .9 when based on all 32 data points. However, this seems unfairly weighted by the 15 points to the left of the line I-I near the origin. The standard deviation and multiple correlation coefficient as recomputed on the basis of the origin and data points to the right of the line I-I, excluding point 2a, are .06 ppm and .7 respectively.

As a test of the hypothesis that low-rise sources dominate the  $\text{SO}_2$  data, Fig. 2.3 was replotted in Fig. 2.4, using all residential and commercial emissions. It is evident that points representing those quadrants most affected by this modification are moved far to the right and appreciably below the regression line from Fig. 2.3. Clearly, emissions from high rise apartment buildings in quadrants 4b, 4c, 4d, 2b, 2d and especially 2a do not contribute proportionally to  $\text{SO}_2$  concentrations near the ground.



112-9756

Fig. 2.4 Quadrant Survey- $\text{SO}_2$  Levels vs. Residential (All Buildings) and Commerical Emissions. Jan.-Feb.-March 1967.  $W_s = 5.5-9.5$  mph. Heating Hours. Stability Class 4

From the results shown in Fig. 2.3, one may hope to assess the significance of utilities and industry as major consumers of coal, and therefore, their potential responsibility for high  $\text{SO}_2$  levels. The data points of interest involve winds from isolated power plants such as the Northwest station or from the industrial corridor along the Stevenson Expressway (see Fig. 2.2).

The significance of these large sources is supported by several observations:

- 1) TAM 3 records the same  $\text{SO}_2$  levels with winds from the SW as from the NE, even though the SW quadrant has only 1/3 of the  $\text{SO}_2$  emission rate;
- 2) TAM 2 records comparatively high readings for winds from the Southwest quadrant, which includes the Northwest CECO plant (2 miles away) and most of Chicago's industry (about 8 miles away);
- 3) TAM 5 NW receives  $\text{SO}_2$  from two CECO plants, the sanitary district plant and local industries, including the nearby American Can Company plant. By comparison with point 5c, these sources might account for .1 ppm on a typical Chicago day;
- 4) Winds from the north at Stevenson Elementary School (8a, d) seem to be associated with slightly higher  $\text{SO}_2$  levels than those from the south.

The following observations are in contrast to the above, and show that not all TAM stations are significantly affected by  $\text{SO}_2$  contributions from large point sources:

- 1) Hyde Park's NW quadrant (4d) which views the industrial corridor is nearly identical to quadrant 4c in  $\text{SO}_2$  concentrations and residential emission density is higher;
- 2) The SE and SW quadrants at Austin (TAM 7) are not significantly out of line with the general linear relationship shown in Fig. 2.3, even though this station is only five miles from the industrial corridor;
- 3) TAM station 6, NE should be, but is apparently not affected by the Calumet and Stateline CECO plants as well as by the more distant Gary-Hammond industrial complex.

From the above, it appears that contributions from industry and utilities to ground level  $\text{SO}_2$  concentrations are likely to fall in the range of .05 to .1 ppm. This is substantiated by the observed deviations from the regression line in Fig. 2.3, by the standard deviations associated with the individual temperature correlations listed in Table 2.2, and by the point source calculations presented in Section 2.3.

In conclusion, it should be emphasized that this survey has been restricted to neutral or slightly unstable days typified by Brookhaven Class B1 and Turner's Classes 3 and 4. Large point sources may be quite important in any estimation of  $\text{SO}_2$  levels during the break-up of nocturnal inversions, lake breeze regimes, or other unusual meteorological situations which can be associated with high pollution incidents.

## 2.4 Development and Validation of Prediction Algorithms

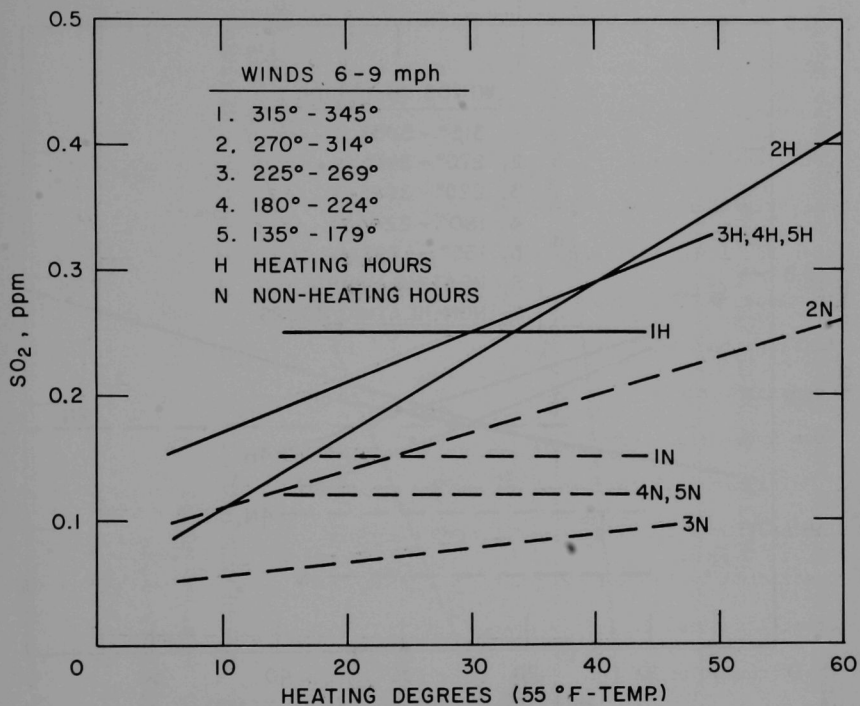
The demographic profile of Chicago is a dominant factor in determining  $\text{SO}_2$  levels. This is evidenced by the strong correlation in Figure 2.3 of  $\text{SO}_2$  concentrations and residential and commercial densities, where the correlation is based on 90 degree wind sectors. In order to investigate the possible heterogeneity of land use, even within a single square mile, and as a first step toward establishing directional sensitivity to more distant concentrations of large point sources, it seems desirable to consider wind sectors on an octant basis. A finer set of wind direction bands with a lower bandwidth limit of about  $30^\circ$  could be considered. This limit is defined by uncertainties in the specification of wind direction by Midway Airport and TAM aerovanes. On the other hand, the  $\text{SO}_2$  emission inventory of area sources is not fine enough to permit consideration of even  $45^\circ$  sectors, although, if desirable, a more detailed emission distribution survey could be undertaken, since only a limited area about TAM Stations 2, 3, 4, and 5 need be studied.

### 2.4.1 Octant Survey

An octant survey ( $135^\circ$ - $180^\circ$ ,  $180^\circ$ - $225^\circ$ ,  $225^\circ$ - $270^\circ$ , and  $270^\circ$ - $315^\circ$ , (other wind directions being from Lake Michigan) similar to the quadrant survey described previously has been assembled. In both efforts, data for all hours was analyzed and linear regressions performed with heating degrees ( $55^\circ\text{F}-\text{T}$ ) as the independent variable. However, in the octant

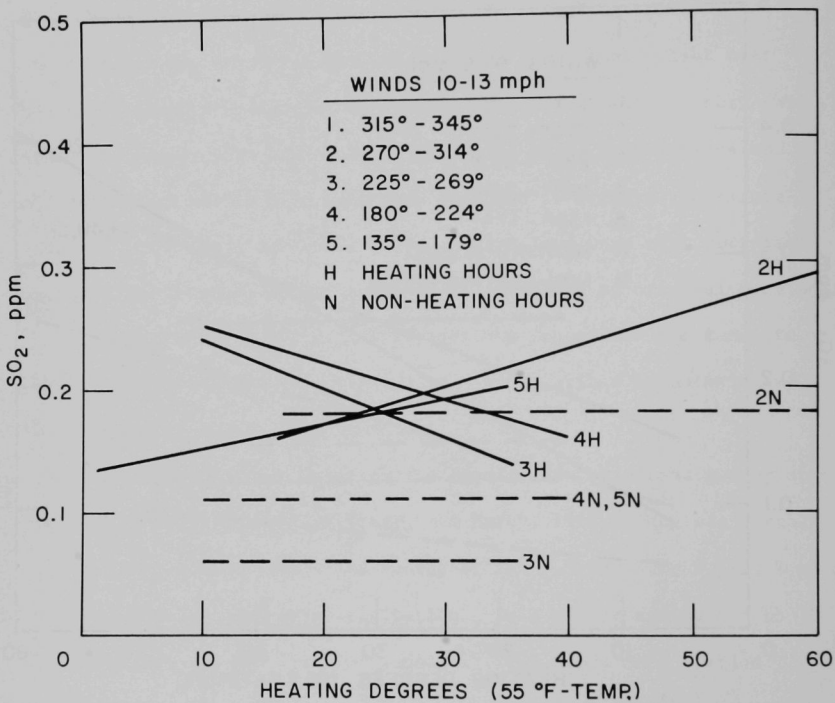
correlations, the independent variable was redefined to give more weight to data points at low temperatures. Since less than 10% of the hours analyzed have temperatures below 15°F, these data points were dominated in the linear regression by the mass of winter temperatures in the 25-32°F range. Yet these few low temperature days are associated with higher fuel use and often with greater atmospheric stability, both of which imply higher SO<sub>2</sub> levels. Thus, in order to give equal weight over the whole temperature scale, as opposed to equal weight for each data hour, the temperature scale was divided into three degree bands and all data hours within each band were averaged to yield a representative SO<sub>2</sub> level for that temperature. Regressions were then performed on these SO<sub>2</sub> averages rather than on the multitude of original data points. This approach clearly emphasizes temperature dependence and tends to suppress perturbations in SO<sub>2</sub> level due to variations in emissions from industrial and utility sources.

Figures 2.5 through 2.8 show the results of the octant survey about TAM station 4 for January, February and March, 1967. Data was further restricted by the met set: wind speeds at TAM 4 5.5-9.5 or 9.5-13.5 mph, stability class 4, and no precipitation. In a manner equivalent to the formulation of the "janitor function", the hours were divided into "heating hours" (6-23) and "non-heating hours" (24-6). Separate regressions were performed on these two sets, with heating degrees as the independent variable. Details for sectors 225-270° and 270-315° at medium wind speeds appear in Figs. 2.7 and 2.8. Most of the original



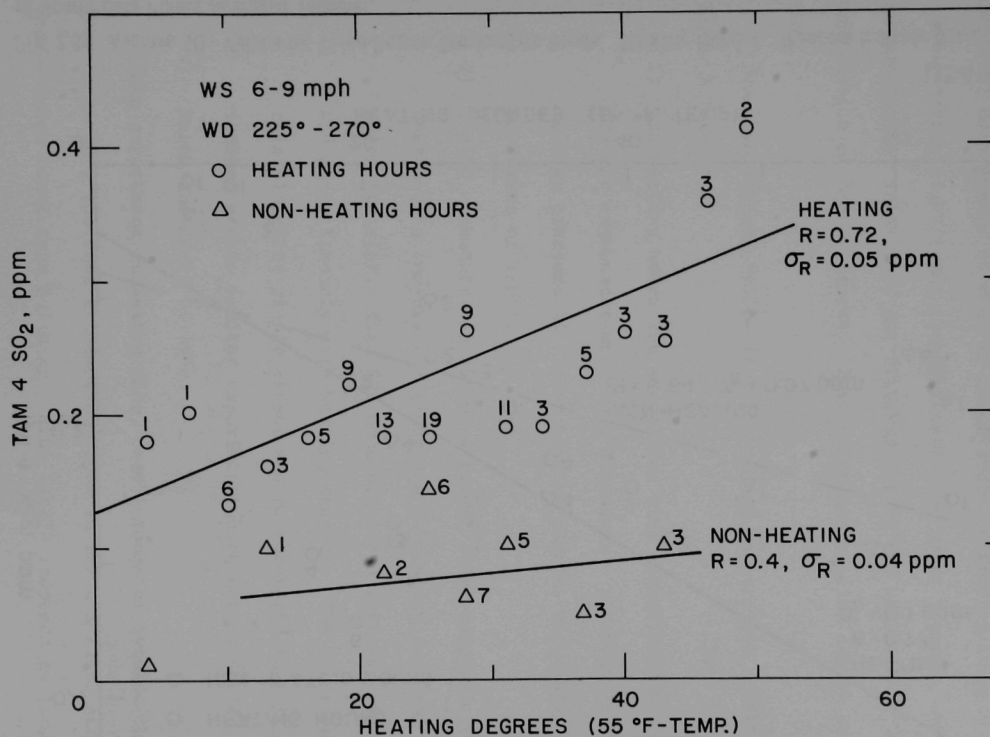
112-9757

Fig. 2.5 Regression Lines for Tam 4. Jan.-Feb.-March 1967. Stability Class 4. No Precipitation



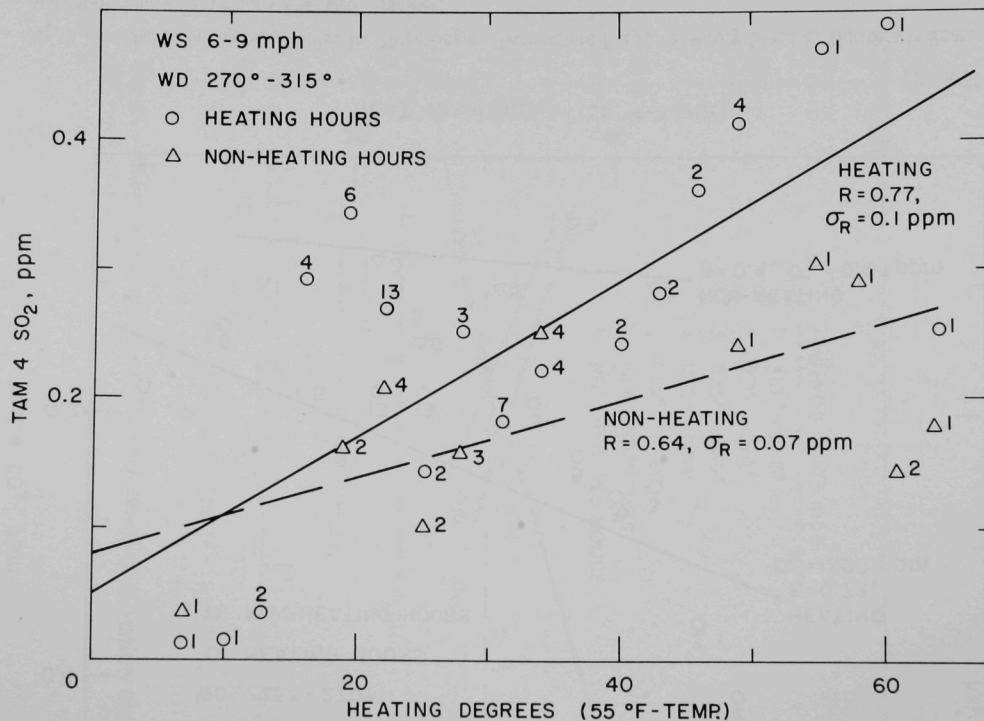
112-9758

Fig. 2.6 Regression Lines for Tam 4. Jan.-Feb.-March 1967. Stability Class 4. No Precipitation



112-9759

Fig. 2.7 Tam 4 Average SO<sub>2</sub> Values for Three Degree Temperature Bands. Stability Class 4. Numbers Indicate Number of Hourly Data Points Averaged Together.



112-9760

Fig. 2.8 Average  $SO_2$  Values for Three Degree Temperature Bands. Stability Class 4. Numbers Indicate Number of Hourly Data Points Averaged Together.

data points for medium winds fell into these sectors. The values plotted in Figs. 2.7 and 2.8 represent from 9 to 19 hourly  $\text{SO}_2$  averages with standard deviations less than  $\pm .1$  ppm. In some cases, the total range of original data points at a given temperature is greater than .4 ppm, indicating either significant contributions from point sources, unusual meteorological conditions not filtered out by the met set, or a combination of these effects. Instrument malfunction cannot be ruled out.

Two observations follow from the strong temperature correlations in Figs. 2.7 and 2.8:

- 1) Non-heating hours are associated with significantly less  $\text{SO}_2$  and are somewhat temperature dependent - possibly in response to high pressure 24 - hour heating plants, especially north - northwest of TAM 4.
- 2) The  $\text{SO}_2$  concentrations show a rather level response to a decrease in temperature (increase in heating degrees) until just below freezing. Then  $\text{SO}_2$  concentrations increase rapidly and quite linearly with heating degrees. The first part of this piecewise linear effect was corroborated in part by the limited stoker monitor experiment which was conducted during March and April of 1968.

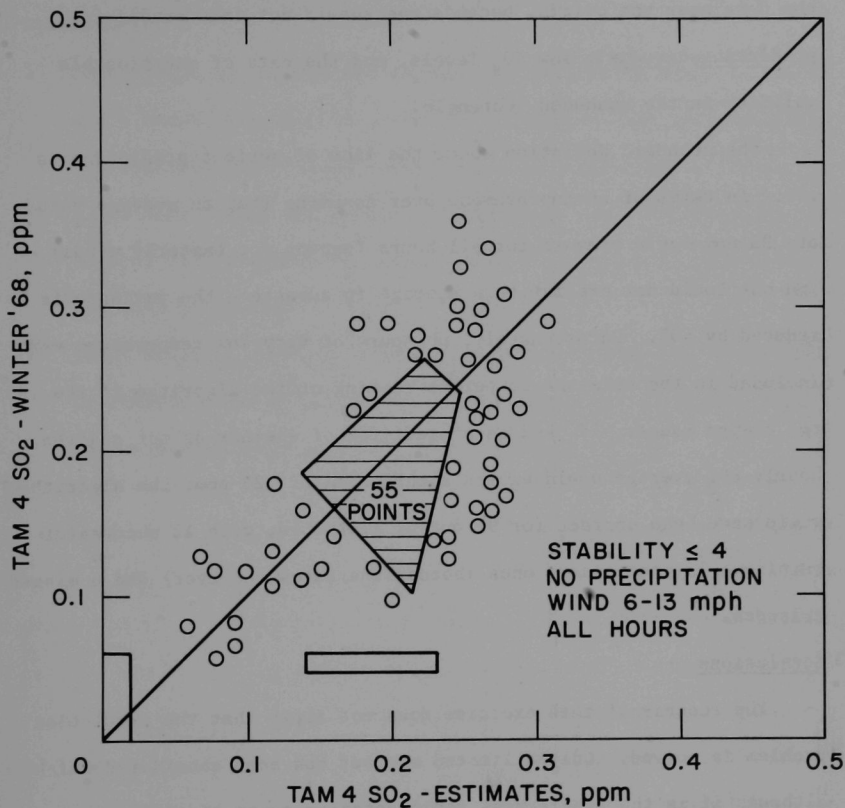
This experiment indicated that, over a range of outside temperatures from 25 to 50°, the fuel consumption rates in the six flat, and especially in the large court type building, show little response to temperature

except during the early morning heat-up period. Approximating the complete temperature range by a single linear fit will therefore tend to underpredict  $\text{SO}_2$  levels at low temperatures, despite efforts made to equalize the importance of each temperature by the aforementioned averaging procedure.

#### 2.4.2 Regression Analysis Results

The twenty regression lines (some of them superimposed) are displayed in Figs. 2.5 and 2.6.. In the high wind category (Figure 2.6), the regression lines corresponding to WNW, WSW, and SSW winds were each based on about 80 original data hours; however only the WNW sector had data over a large temperature range, as indicated by the length of the regression lines in the figures. No physical explanations for the negative slopes of lines representing WSW and SSW sectors in Fig. 2.6 is apparent.

Considering the regression line in Figs. 2.7 and 2.8 as representing an algorithm for predicting  $\text{SO}_2$  levels at Hyde Park (TAM 4) for hours within the prescribed met set, one can then validate the model by predicting corresponding  $\text{SO}_2$  concentrations for winter of 1968. The success of this approach is demonstrated in Fig. 2.9. The central shaded area represents uniform spreading of fifty-five data points. The rectangle at the origin represents data for winds off the lake which are predicted as zero, but which occasionally yield concentrations as high as .08 ppm. The narrow rectangle at .05 ppm represents two days in a block of 5 consecutive days for which the  $\text{SO}_2$  levels at TAM 4 were recorded as a



112-9761

Fig. 2.9 Prediction of Jan.-Feb.-1968 SO<sub>2</sub> Levels by Algorithms Derived from 1967 Data.

steady .05 ppm, regardless of temperature, wind direction, time of day or degree of atmospheric stability. DAPC personnel feel that these data points are probably invalid. In our evaluation of the predictive capability of the set of regression equations, we have disregarded both the data near the origin, because one should not take credit for predicting extremely low  $\text{SO}_2$  levels, and the data of questionable validity in the unshaded rectangle.

The standard deviation about the line of perfect prediction is .06. In terms of an improvement over assuming that an average value of .23 ppm would prevail for all hours (except for easterly winds) - and one could not predict this average in advance - the variance is reduced by 40%. Unfortunately, no hours of very low temperature were included in the data set to permit testing of the algorithm in the .35 to .45 ppm range. If used as a predictor of whether or not a given hourly  $\text{SO}_2$  average would exceed a threshold of .25 ppm, the algorithm would have been correct for 92 out of 110 hours, with 12 successful warnings, 13 unnecessary ones (borderline cases, however) and 6 missed episodes.

#### 2.4.3 Conclusions

The success of this exercise does not imply that the prediction problem is solved. Only a limited met set has been considered which, although it is the single most representative range of meteorological conditions in Chicago, still excludes many important pollution regimes

including nocturnal inversions, lake breezes, and stagnation periods. These meteorological regimes, although less common than that investigated here, signal periods of high  $\text{SO}_2$  levels.

From this point, there appear to be two directions which must be explored.

- 1) Development of temperature regressions similar to those in the TAM 4 octant survey. If these are considered baseline standards, one can seek significant deviations - in particular, prolonged (2, 3 hours) high  $\text{SO}_2$  levels. Presumably, the meteorological conditions and/or nonheating source effects peculiar to each episode can then be defined.
- 2) Point sources, especially under atmospheric conditions which tend to inhibit plume rise, may be factored into the prediction algorithms. This prospect is discussed in the following section.

## 2.5 Pollution Incident Frequency Survey

As a part of the effort to develop an air pollution profile for Chicago, a series of  $\text{SO}_2$  incident scans were performed on 15 months of meteorological and air quality data in the master computer file. The objective of this survey was to estimate the time and space distribution of high ambient  $\text{SO}_2$  concentrations throughout the Chicago "pollution year."

In structuring this series of data scans, it was necessary to take account of the fact that no universally acceptable biomedical definition of an  $\text{SO}_2$  "incident" exists at present. That is, no medical authority has developed a fully credible set of  $\text{SO}_2$  dose rate thresholds which could be used to define a pollution incident in terms of an allowable maximum ambient  $\text{SO}_2$  concentration over a specified interval of time. Several years ago, the U.S. Public Health Service (ref. 8) published a set of  $\text{SO}_2$  dose rate curves which, if generally accepted, could have served as standard criteria for the identification of an  $\text{SO}_2$  incident. These original PHS standards were, however, generally criticized as being excessively stringent and inadequately validated, hence it has not proven feasible to base a practical air pollution abatement program on them.

More recently, on the basis of a series of statistical biomedical studies performed in Chicago on 12 hour ambient average  $\text{SO}_2$  concentrations, (Carnow, et al) the Chicago DAPC has adopted an approximate standard definition of  $\text{SO}_2$  incident based on a dose rate of 0.3 parts per million for three consecutive hours. The question of what constitutes an incident is, nevertheless, still far from settled. In order to characterize urban air

pollution potential, it is, therefore, necessary to parameterize a study of incident frequency in terms of various definitions of an acceptable dose-rate threshold. This is particularly true in the case of a fairly well ventilated region, wherein ambient  $\text{SO}_2$  concentrations averaged over relatively long time periods (days, weeks or months) are apt to be deceptively low. Chicago has, of course, recorded impressively high local peak concentrations ( $>1$  PPM) but these pollution spikes are difficult to interpret in terms of their biomedical significance. A realistic assessment of "pollution potential" must therefore be based on the susceptibility of the city to  $\text{SO}_2$  incidents, that is, on the frequency, duration, severity and time-space distribution of high  $\text{SO}_2$  concentrations.

The initial series of master data file searches described here were based on four ambient  $\text{SO}_2$  concentration levels, 0.2, 0.3, 0.4 and 0.5 PPM, and on four time intervals, 1 hour, 6 hours, 12 hours and 18 consecutive hours. Thus, the frequency distribution of 16 different  $\text{SO}_2$  dose-rates was investigated. The selection of 6 hour time increments was predicated on the empirical (but unproven) assumption that it would probably not be economically or operationally feasible to attempt a pollution abatement exercise for an incident of duration less than six hours.

The results of this 15 month frequency survey are presented in Tables 2.4, 2.5, 2.6 and 2.7, where incident frequencies are recorded for each TAM station for each month from January 1966 through March 1967. Figure 2.2 shows the TAM network and indicates the distribution of the receptor stations throughout the city. These tables depict the number of

occasions during each month that the ambient  $\text{SO}_2$  concentration at each TAM receptor exceeded a given level for a given time interval. Some of the high concentration hours are therefore counted more than once. For example, an 0.3 PPM hour in January 1966 which was counted in Table 2.4 as an individual incident could also be recorded as a part of a six consecutive hour incident in Table 2.5. Similarly, a six consecutive hour incident recorded in Table 2.5 might also be counted as part of a 12 hour incident in Table 2.6 and an 18 hour incident in Table 2.7.

Although tables 2.4 through 2.7 serve as an effective means of presenting a month-to-month comparison of Chicago's  $\text{SO}_2$  incident pattern, the spatial distribution of pollution potential is more evident in tables 2.8 through 2.11, which summarize the incident frequencies experienced at each TAM station over the entire 15 month period considered in this survey. These sets of tables can be employed to assess the time-space distribution frequency of Chicago  $\text{SO}_2$  incidents of varying degrees of severity. Logarithmic interpolation between the tabulated concentrations and/or exposure times is feasible if other dose-rates than those presented in the tables are of interest.

An examination of the 15 month incident frequency tables described above leads to the following conclusions:

1. Seasonal Concentration A clear seasonal trend is evident for all dosage levels and at all TAM stations. The majority of all  $\text{SO}_2$  incidents occur during the four month long heating season which extends from December through March. This may be attributed to two related

TABLE 2.4  
Greater than 0.5 PPM

1966-67

1 Hour SO<sub>2</sub> Concentrations

TAM Station	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
1	0	2	0	1	0	0	0	0	0	0	1	1	0	0	0
2	8	1	0	2	0	0	0	0	0	1	4	0	4	10	0
3	52	46	4	0	1	1	3	1	0	7	36	114	77	117	24
4	173	46	8	2	1	0	0	0	0	7	8	4	1	12	6
5	34	7	3	1	0	0	0	0	0	0	0	0	0	0	0
6	61	0	0	4	0	0	0	0	0	0	0	0	0	0	0
7	3	1	15	1	1	0	0	0	1	0	2	5	5	1	0
8	1	4	0	1	0	0	0	0	0	0	0	0	0	0	0

Greater than 0.4 PPM

1	0	5	1	6	0	0	0	0	0	0	3	1	1	1	0
2	13	1	0	10	2	0	0	0	0	1	4	0	11	23	5
3	95	83	14	7	3	3	3	2	0	20	69	241	158	225	52
4	266	81	20	9	3	0	0	0	2	13	11	14	3	46	23
5	57	10	7	2	0	0	0	1	0	0	1	0	2	1	3
6	83	3	1	4	1	1	0	0	0	0	0	1	0	0	0
7	15	3	37	2	4	1	0	0	3	3	9	13	17	13	2
8	9	5	0	1	0	0	0	0	0	0	0	0	0	0	0

Greater than 0.3 PPM

1	1	18	7	6	0	0	0	0	0	1	11	3	3	4	5
2	25	11	9	17	7	0	0	0	0	2	18	2	23	65	24
3	195	167	55	35	7	14	5	13	5	44	169	402	274	358	95
4	381	142	76	35	10	1	0	0	7	27	28	50	11	149	49
5	120	36	15	6	0	1	0	2	0	0	5	6	3	6	7
6	128	12	2	7	8	3	1	0	0	0	1	5	0	1	1
7	30	11	90	9	11	2	1	2	12	6	36	36	31	41	14
8	28	10	0	1	0	0	0	0	0	0	0	9	0	3	0

Greater than 0.2 PPM

1	11	31	26	20	5	2	0	0	1	3	25	14	17	18	9
2	92	44	28	25	15	1	4	5	3	13	70	26	101	135	56
3	320	307	183	92	39	36	12	26	21	92	325	577	453	543	184
4	489	201	154	95	38	6	5	30	21	75	129	170	109	385	83
5	249	93	39	16	9	4	0	5	0	7	11	22	13	32	25
6	191	42	8	20	22	10	2	0	7	1	7	13	2	21	18
7	116	62	177	34	48	6	7	9	25	16	81	114	99	105	35
8	77	22	4	14	8	0	0	1	1	2	4	27	9	22	15

TABLE 2.5  
Greater than 0.5 PPM

### 6 Hour SO<sub>2</sub> Concentrations

1966-67

[illegible]

Greater than 0.4 PPM

[illegible]

Greater than 0.3 PPM

[illegible]

Greater than 0.2 PPM

[illegible]





Total Number of One Hour SO<sub>2</sub> Incidents (1966-67)

<u>TAM Station</u>	<u>G.T.O.2 PPM</u>	<u>G.T.O.3 PPM</u>	<u>G.T.O.4 PPM</u>	<u>G.T.O.5 PPM</u>
1	182	59	18	5
2	618	203	70	30
3	3210	1838	975	483
4	1990	966	491	268
5	525	207	84	45
6	364	169	94	65
7	934	332	122	35
8	206	51	15	6

TABLE 2.9

Total Number of Six Hour SO<sub>2</sub> Incidents (1966-67)

<u>TAM Station</u>	<u>G.T.O.2 PPM</u>	<u>G.T.O.3 PPM</u>	<u>G.T.O.4 PPM</u>	<u>G.T.O.5 PPM</u>
1	2	1	0	0
2	41	7	3	0
3	358	180	76	23
4	206	87	41	21
5	35	12	6	4
6	27	15	9	6
7	61	13	2	0
8	6	0	0	0

TABLE 2.10Total Number of 12 Hour SO<sub>2</sub> Incidents (1966-67)

<u>TAM Station</u>	<u>G.T.O.2 PPM</u>	<u>G.T.O.3 PPM</u>	<u>G.T.O.4 PPM</u>	<u>G.T.O.5 PPM</u>
1	1	0	0	0
2	6	1	0	0
3	136	56	22	5
4	75	24	10	6
5	10	4	1	1
6	8	5	2	1
7	10	2	0	0
8	0	0	0	0

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TABLE 2.11Total Number of 18 Hour SO<sub>2</sub> Incidents (1966-67)

<u>TAM Station</u>	<u>G.T.O.2 PPM</u>	<u>G.T.O.3 PPM</u>	<u>G.T.O.4 PPM</u>	<u>G.T.O.5 PPM</u>
1	0	0	0	0
2	0	0	0	0
3	65	22	7	1
4	35	13	5	2
5	5	2	1	1
6	5	3	2	0
7	2	0	0	0
8	0	0	0	0

---

factors. High sulfur content coal and oil are used extensively for a commercial and residential space heating, industrial processing and electrical power generation during the winter months. In summer, on the other hand, fuel use for space heating is virtually curtailed and the larger industrial plants and most of Chicago's power generating capacity are converted to the use of natural gas, which is available at "dump rates" during the nonheating season. This concentration of  $\text{SO}_2$  incidents in the heating season is evident in the following table which presents the ratio of the number of one hour, 0.2 PPM incidents encountered at each TAM station during December, January, February and March to the total number of such incidents recorded during the entire 15 month period.

TAM Station	1	2	3	4	5	6	7	8
Heating Season Incident Ratio	0.69	0.77	0.79	0.79	0.90	0.81	0.75	0.85

As indicated in the table, between 69% and 90% of all one-hour, 0.2 PPM incidents which occurred during this 15 month period were concentrated in the four heating season months. It is evident from tables 2.4 through 2.7 that this seasonal concentration would be accentuated if higher dosages than this minimum level were similarly tabulated.

2. Spatial Concentration Tables 2.8 through 2.11 indicate the relative susceptibility of each of the eight TAM "regions" to  $\text{SO}_2$  incidents. A significant degree of nonuniformity is evident in the spatial distribution of incidents recorded during the 15 month survey period.

The most noteworthy feature of this set of tables is the clear predominance of TAM stations 3 and 4 in terms of incident frequency and severity. TAM station 3 is centrally located in the Chicago loop business district, and as such, is not only surrounded by a cluster of large commercial space heating sources, but is situated directly NE of a major concentration of industrial plants and a line formed by the three largest electric power plants within the city limits. Since the prevailing winds in the Chicago area are southwesterly, a high incident frequency due to this industrial-utility concentration and to local space heating effects is to be expected at TAM station 3.

The incident frequency recorded at TAM station 4 in the Hyde Park residential area is little more than half of that associated with station 3, but twice that of station 7 - the next most significant receptor. The Hyde Park area has been studied in some detail during the course of this program, and the dominant type of  $\text{SO}_2$  source for this section of the city has been fairly well established through a statistical study of local air quality data and an emission inventory of the area. These analyses indicate a fairly strong correlation between ambient  $\text{SO}_2$  concentrations and the emission pattern associated with a large, local concentration of coal and oil-fired residential buildings which characterize

this relatively old section of the city. These moderate-sized residential structures, which release  $\text{SO}_2$  at a few stories above ground level, appear to be the dominant sources affecting local ambient  $\text{SO}_2$  concentration, while emissions from utilities and industrial plants to the west and northwest are difficult to detect against the space heating background.

TAM stations 7, 6, 5 and 2 experience  $\text{SO}_2$  incidents with a frequency ranging from 50% to an order of magnitude less than do stations 3 and 4. These stations are sited in mixed industrial - residential areas which are characterized by fairly extensive use of natural gas for residential space heating or by a predominance of fairly high rise residential structures.

Station 7 is centrally located and adjacent to the Cicero, Illinois industrial concentration, but the relative scarcity of southeasterly winds minimizes the influence of the major utility - industrial concentration which appears to contribute to the high TAM station 3 frequency record. As a result, this station runs a poor third in terms of incident frequency.

Station 5 is approximately the same distance from the central utility and industrial source cluster as station 3, but since the source cluster is located to the Northeast of TAM 5, it also appears to benefit from the prevailing southwesterly flow.

Station 6, in the extreme southeast of the city, is sited relatively near a second concentration of utility and industrial plants,

(see Fig. 2.2) and is adjacent to the Gary-Hammond industrial area, but again, the relative scarcity of southeasterly and easterly winds in the Chicago area tends to insulate this receptor from these major local source concentrations.

Station 2, in the Northeast section of the city, is in a mixed industrial - residential area which contains a large concentration of high rise residential structures. The prevailing southwesterly flow would tend to transport  $\text{SO}_2$  from the central utility - industrial cluster into this section, but the average dosages tend to be low because of the comparatively large transport distances involved. This is evidenced by the relatively high ratio of  $>0.2$  PPM incidents to  $>0.5$  PPM incidents at station 2, compared to stations 3 or 4 where localized source effects could be expected to be more significant. The incident frequency tables indicate that, while station 2 experienced a considerable number of low concentration events, relatively few high concentration incidents which would presumably be caused by fairly nearby  $\text{SO}_2$  sources, are recorded.

Stations 1 and 8 are the least susceptible to the occurrence of  $\text{SO}_2$  incidents, and both are located in relatively "clean" peripheral areas of the city. These stations experience  $\text{SO}_2$  incidents at least one order of magnitude less frequently than do stations 3 and 4, and both are characterized by a fairly high ratio of low to high concentration frequencies - indicative of the relative scarcity of large, local  $\text{SO}_2$  source concentrations.

On the basis of the incident frequency tables, it appears that the city can be divided, rather roughly, into three air pollution dose rate regions. These are:

- 1) A high dose rate inner city region monitored by stations 3 and 4.
- 2) An intermediate dose rate ring monitored by stations 2, 5, 6 and 7.
- 3) A low dose rate outer ring monitored by stations 1 and 8.

It therefore appears that the development of effective incident abatement strategies for Chicago, as well as the formulation of long-range pollution emission control plans, should reflect priorities based on the geographical and seasonal localization of  $\text{SO}_2$  incidents indicated in this survey. The recently enacted (June 1968) Chicago  $\text{SO}_2$  emission control ordinance represents an initial attempt to accomplish long range control through a three-year "rollback" program which should ultimately result in a 50% reduction in average annual  $\text{SO}_2$  concentrations. This would mean that, if the ordinance were enforced equally for all  $\text{SO}_2$  sources in Chicago, the frequency distribution of 0.2 ppm incidents in 1973 would be approximately the same as that of 0.4 ppm incidents in 1966-67, etc. It is not yet clear that uniform enforcement of an emission control law will be feasible. Enforcement of such legislation in certain sections of the city may prove difficult.

In the long run, the most significant aspect of this incident distribution survey may be its implications for the control of the maximum allowable area density of  $\text{SO}_2$  sources in the model city of the future. If it should not prove feasible to identify the local ambient

concentrations due to specific sources, and if the enforcement of universal emission control laws of the kind recently enacted in Chicago should prove impractical, then the only remaining long range solution to the air pollution problem - for  $\text{SO}_2$  and other pollutants - is through the use of zoning ordinances designed to insure that excessive pollution source concentrations cannot be created in areas susceptible to the generation of incidents of the kind evaluated here.

## 2.6 Plume Studies

### 2.6.1 Major Point Sources

The fundamental regression equation (Eq. 1) assumes linear superposition of temperature dependent patterns and contributions from significant upwind point sources. As was discussed in previous reports, the decision as to the importance, and therefore the inclusion in Eq. 1, of a given point source is first to be made on an order of magnitude basis using a traditional gaussian plume formulation. This section describes the assumptions incorporated in a computer code PLUME used to estimate the contributions of various point sources to the SO<sub>2</sub> readings at TAM stations. Upon their request the Commonwealth Edison Company has been provided with a copy of this code to assist them in their independent evaluation of power plants.

The geometry of the problem is somewhat general in that, although only constant wind direction is considered, the input allows arbitrary source and detector coordinates, which, for convenience, are stored in terms of source and detector identification numbers. Thus, for any given pair of source and detector numbers (listed in Appendix II of ref. 2), the appropriate coordinates are found and then resolved into downwind and crosswind directions according to the specified wind direction.

Plume rise is estimated according to the Carson - Moses formula:<sup>(9)</sup>

$$\Delta H = A * 5.35 * Q_s^{1/2} / U \quad (3)$$

where  $Q_s$  is the thermal output of the stack in kilocalories/sec (assumed 20% of the thermal power of the plant) and  $U$ , the wind speed in m/sec at the top of the stack. Momentum effects (the first term in the formula from ref. 2) are negligible compared to thermal buoyancy for most large sources. The constant  $A$  takes on the value 2.6, 1 or .7 dependent upon whether the atmosphere is classified as unstable, neutral, or stable.

The plume equation:

$$x \left( \text{ppm SO}_2 \right) = .59 \frac{Q_{\text{plant}} \left( \frac{\text{Kcal}}{\text{sec}} \right)}{\sigma_y \sigma_z U} \left\{ \exp \left[ - \frac{y^2}{2\sigma_y^2} \right] \right\} \left\{ \exp \left[ - \frac{(z - H_{\text{TAM}})^2}{2\sigma_z^2} \right] \right\} \left\{ \exp \left[ - \frac{(z + H_{\text{TAM}})^2}{2\sigma_z^2} \right] \right\} \quad (\text{mks units}) \quad (4)$$

assumes 3% sulfur coal with a heating value of  $10^4$  Btu/lb.  $H_{\text{TAM}}$  is the height of the air intake;  $z = H_{\text{stack}} + \Delta H$ .

Following Turner, <sup>(3)</sup>  $\sigma_y$  and  $\sigma_z$  are defined in terms of time of flight  $t = x/u$  and approximated here by simple power relationships:

$$\begin{aligned} \sigma_y &= a_{iy} t^{b_{iy}} \\ \sigma_z &= a_{iz} t^{b_{iz}} \end{aligned} \quad (5)$$

where the  $a$ 's and  $b$ 's depend upon the stability index  $i$ .

TABLE 2.12 Point Source Contributions to TAM Stations  
Directly Downwind [WS = 10 mph]

	Fisk on TAM 4	Crawford on TAM 4	UC on TAM 4	Northwest on TAM 2	Crawford on TAM 7
max. $Q_{plant}^a$ (M BTU/hr)	3300	3000	90	830	3000
# stacks	1 <sup>e</sup>	4	2	2	4
stack height (ft)	450	300 <sup>f</sup>	200	300	300
downwind distance (mi)	6.0	7.7	.7 <sup>g</sup>	1.7	4.2
plume rise <sup>b</sup> (ft)	2200	2100	400	1100	2100
$\sigma_z$ (ft) <sup>c</sup>	1700	2100	200	500	1200
$\sigma_y$ (ft)	2600	3300	400	900	1900
max. ppm <sup>d</sup> per stack	.04	.04	.02	.03	.03
max. ppm all stacks	.04	.16	.04	.06	.12
avg. ppm all stacks - 30° wind sector	.01	.04	.01	.02	.04
plume rise (ft)	600	600	100	300	600
$\sigma_z$ (ft)	400	400	100	150	300
$\sigma_y$ (ft)	1300	1600	200	400	1000
max. ppm per stack	.02	.1	.03	~0	.02
max. ppm all stacks	.02	.4	.06	~0	.08
avg. ppm all stacks - 30° wind sector	.002	.06	.01	~0	.01

a) Based on  $Q_{stack} = .2 \times Q_{plant}$ . Calculations assume 3% sulfur coal at  $10^4$  Btu/lbm.

b) Carson - Moses (ref. 9).

c) Turner (ref. 3).

d)  $\mu$  moles/mole.

e) Calculation does not consider the 292 foot stacks which are used less frequently.

f) Conservative value since two stacks are 375 feet high.

g) U.C. distance is actually about 3 mi. These concentrations therefore represent an upper bound on U.C. at TAM 4.

TABLE 2.13 Dispersion Parameters. Approximations to Curves by Turner<sup>(3)</sup>

Stability Class, i	$a_y$ (m)	$b_y$	$a_z$ (m)	$b_z$
3	.8	.9	.5	.9
5	.4	.9	.5	.7

Table 2.13 summarizes five calculations representative of the major point sources (CECO plants) and of large stacks close by TAM stations (University of Chicago). For both unstable and stable cases, the rows in Table 2.12 entitled "max. ppm per stack" and "max. ppm all stacks" show that the centerline concentrations due to these plants are near and for Crawford above the threshold of detection. This threshold is a somewhat nebulous level determined by several factors: instrument sensitivity which is probably better than  $\pm 0.03$  ppm,<sup>(10)</sup> the ambient level of  $SO_2$  at the TAM station, and most important the standard deviation of the TAM data about the temperature regression line (if a significant one exists). This standard deviation represents background noise, independent of temperature from which the signal must be filtered.

The signal at TAM 4 from Crawford is estimated at a maximum value of .04 to .4 ppm; plant at full power and wind focused on Hyde Park - and at this level it should be apparent in the TAM 4  $SO_2$  data. However, in order to account for inaccuracies in TAM and Midway records of wind direction<sup>\*</sup> and to obtain adequate statistics, it will probably be

\* Midway measurements for each hour are at best one minute averages of the aerovane dial. TAM measurements, while electronically averaged throughout the hour, are subject to building interferences.

necessary to include in the regression all data points within a wind direction band of from  $15^\circ$  to  $20^\circ$  either side of the bearing from source to TAM station.

As the regression equation (Eq. 1) is presently formulated, each coupling coefficient is based on source emissions equally weighted for all winds within the allowable band. For example, assume Crawford is the only  $\text{SO}_2$  source in Chicago, and that because of the uncertainty of our wind direction predictions, two data points are included, both with Crawford at full power,  $Q_{\max}$ . One data point might correspond to a centerline concentration of .16 ppm while the other for a wind only  $5^\circ$  off center (these are hourly averages of wind direction) might be .06 ppm. The regression matrix would appear as follows,

$$.16 = C_0 + K_1 Q_{\max}$$

$$.06 = C_0 + K_1 Q_{\max} .$$

The best fit to the coupling coefficient  $K_1$  would therefore be representative of the average of the Crawford plume over the two wind directions.

The effect of the size of the wind band on the determination of coupling coefficients from point sources can be assessed by assuming that the data is distributed uniformly in wind direction over the allowable band and then averaging the plume equation over this arc. The equation is of the form,

$$\chi = F(z, x/u) e^{-y^2/\sigma_y^2} \quad (6)$$

which for  $y \ll x$ , can be approximated by the angular deviation ( $\theta$ ) from the centerline:

$$\chi \cong F(z, x/u) e^{-x^2 \theta^2 / \sigma_y^2} \quad (7)$$

Thus, for a wind band  $\pm \theta_m$  about the plume centerline:

$$\begin{aligned} \bar{\chi} &= \frac{F(z, x/u)}{\theta_m} \int_0^{\theta_m} e^{-x^2 \theta^2 / \sigma_y^2} d\theta \\ &= \frac{.886 \frac{\sigma_y}{x \theta_m} F(z, x/u)}{\left[ \operatorname{erf} \left( \frac{x \theta_m}{\sigma_y} \right) \right]} \\ &= \frac{.886 \frac{\sigma_y}{x \theta_m} F(z, x/u)}{\quad} \quad \text{for } \frac{x \theta_m}{\sigma_y} \geq 2. \end{aligned} \quad (8)^*$$

For a  $30^\circ$  wind direction band, this averaging process implies mean concentrations of from 10% - 30% of the maximum centerline values (Table 2.12). Thus, hourly contributions from Crawford can easily vary by factor of five within a given data set, even though the plant is operating at a steady power level.

Techniques to deal with this problem in a regression analysis are not yet clear. One can obviously narrow the wind band, but it is clear that mean hourly wind directions and wind profiles of Chicago will never be specified better than  $\pm 10^\circ$  nor would they have much physical meaning

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\* The error function is defined by <sup>(11)</sup>

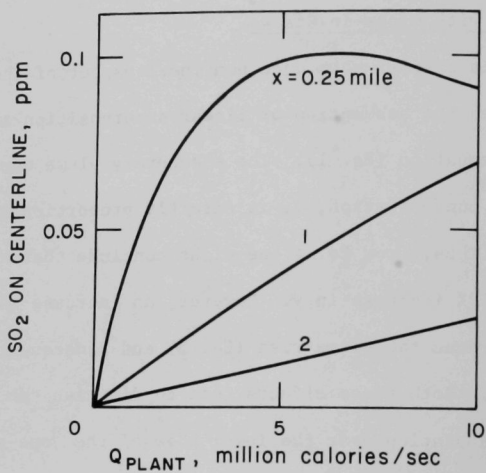
$$\operatorname{erf}(t) = \frac{\sqrt{2}}{\pi} \int_0^t e^{-t^2} dt$$

at lower tolerances. Thus, whether one is predicting  $\text{SO}_2$  contributions directly using a plume equation and verifying by comparison with  $\text{SO}_2$  data, or if one is using our regression approach and correlating  $\text{SO}_2$  data with point source emissions, the uncertainty caused by an inability to specify plume trajectories implies a fundamental uncertainty in the ability to verify the model. The extent of this problem will be studied in the forthcoming quarter.

## 2.6.2 Nonlinear Coupling with Close-in Stacks

This section is a brief note on a nonlinear aspect of the plume model which violates the assumption of linear superposition inherent in the regression equation (Eq. 1). The elementary plume equation shows that the pollution concentration,  $\chi$ , is directly proportional to the pollutant source,  $Q$ . Thus, from Eq. 4 one might conclude that a 10% increase in  $Q$  results in a 10% increase in  $\chi$ . However, an increase in stack emission will also increase the plume rise (Eq. 3) and consequently the mean transport velocity. Both these effects tend to diminish the concentration,  $\chi$ . For a TAM station near the lower edge of the "one-sigma" cone, the effects can be significant.

For the University of Chicago, located about .25 miles from TAM 4, Fig. 2.10 indicates that an increase from half to full power (16 megacalories/sec) raises the centerline contribution at the Hyde Park reception from .085 to .1 ppm. This nonlinearity is anticipated only at short range. Figure 2.10 indicates that an equivalent plant located one mile upwind is likely to be linearly coupled with the receptor.



112-9762

Fig. 2.10 Non-Linear Effect of Plume Rise. Based on a U.C. Stack (200 ft. High with Maximum Output of 6 M Cal/sec). Stability Class 4

## 2.7 Discriminant Analysis Evaluation Tests

The results of a limited series of tests of multivariate discriminant analysis as an analytical tool and as a technique for the development of a receptor oriented air pollution prediction model were presented in the second quarterly progress report. This test series was extended during the third quarter, and a partial validation of the predictive capability of the technique was achieved.

### 2.7.1 Partitioning the Data

The TAM data file was employed to generate a set of six hour average  $\text{SO}_2$  and wind vector values for each of the eight air quality monitoring stations. These averages were developed for the time periods 0900-1500, 1500-2100, 2100-0300 and 0300-0900; thus they correspond to the daylight, evening transition, night and morning transition periods. This subset of data was further partitioned into periods corresponding to the four seasons December - February, March - May, June - August and September - November. This constituted an attempt to artificially sensitize the data to source influences such as space heating emissions and to minimize the effects of variance due to seasonal, climatological phenomena. The data was then partitioned into two air quality classes:  $\text{SO}_2 \geq 0.2$  ppm and  $\text{SO}_2 \leq 0.2$  ppm--a fairly high six hour dose rate when assessed by current standards. A final partitioning of the data into three wind sectors  $0 - 90^\circ$ ,  $90^\circ - 180^\circ$ , and  $180^\circ - 360^\circ$  was made on the basis of the known  $\text{SO}_2$  source distribution pattern relative to the Hyde Park TAM station. This station was selected as the initial object of a pilot

evaluative study of the discriminant analysis technique.

The results of a series of exploratory discriminant analysis test runs which were performed on this body of data are reported in this section of the quarterly report. It is important to note that these tests were preliminary and evaluative in nature - thus the groupings of data described above represented an experimental expedient designed to test a methodology rather than an irrevocable commitment to a course of action. For example, the use of only three discriminant variables and the partitioning of the data about 0.2 ppm into only two SO<sub>2</sub> concentration groups was an arbitrary convenience for this series of tests. If, in fact, this technique should prove to be an effective device for the development of a receptor oriented pollution prediction system, additional discriminators would undoubtedly be involved, and three to five SO<sub>2</sub> bands would be appropriate.

The object of the series of tests described here was to determine how effectively stepwise discriminant analysis could be used to:

- 1) Estimate the correct SO<sub>2</sub> band in terms of the three discriminant variables, wind direction, wind speed and degree day;
- 2) Evaluate the relative significance, as predictors, of the selected discriminant variables;
- 3) Locate and determine the extent of wind sectors associated with consistently high SO<sub>2</sub> concentrations;
- 4) Identify time of day and seasonal effects on ambient air quality and on the discriminant variables.

### 2.7.2 Discriminant Analysis Test Results

A series of test runs were made on the Hyde Park TAM data for the period January 1966 through February 1967. The results of these tests are shown in Tables 2.14 through 2.17. The nomenclature associated with these tables is as follows:

T/S = Time Period/wind sector

WD = Wind direction (deg)

WV = Wind speed (mph)

DD = Degree Day (Based on 65°F)

$\sigma_W$  = Wind direction std. deviation

$\sigma_V$  = Wind speed std. deviation

$\sigma_D$  = Degree Day std. deviation.

The "high," "low" and "total" columns in these tables correspond to the number of data points that were correctly assigned to their respective groups and the total number of data points that were actually contained within each group. For example, the first row of Table 2.14 shows that for time period 1 (0900 - 1500), for data associated with winds in the western hemisphere, the discriminant equations correctly assigned 56 out of 73 data points to the  $SO_2 \geq 0.2$  ppm group while 36 out of 48 data points were correctly assigned to the  $SO_2 \leq 0.20$  ppm group.

The " $SO_2$ " column indicates that the data was partitioned about 0.20 ppm. As shown in Table 2.14, it was necessary to lump all four time periods together for study of NE and SE quadrants, since very few

Table 2.14 Discriminant Analysis Hyde Park Tam Station Winter 1966-67

T/S		WD	$\sigma_W$	WV	$\sigma_V$	DD	$\sigma_D$	HIGH	LOW	TOT.	SO <sub>2</sub>
1	HIGH	273	34	7.7	3.1	45.5	11.1	56	17	73	0.20
	W LOW	253	41	8.9	3.0	33.5	9.8	12	36	48	
2	HIGH	264	33	8.8	3.2	46.0	11.4	46	19	65	0.20
	W LOW	248	43	8.8	3.6	33.7	10.8	18	40	58	
3	HIGH	270	38	8.8	3.5	44.8	11.4	49	23	72	0.20
	W LOW	252	36	9.9	3.3	33.4	9.4	14	34	48	
4	HIGH	281	27	7.7	3.4	47.0	11.0	40	11	51	0.20
	W LOW	253	39	8.8	3.2	35.0	10.1	16	60	76	
1234	HIGH	30	27	4.5	1.5	46.5	6.7	8	0	8	0.20
	NE LOW	25	29	4.3	5.0	33.9	9.7	35	98	133	
1234	HIGH	167	10	6.8	3.2	38.0	11.7	5	2	7	0.20
	SE LOW	135	29	7.8	3.0	34.0	8.9	22	60	82	

Table 2.15 Discriminant Analysis Hyde Park Tam Station Spring 1966-67

T/S		WD	$\sigma_W$	WV	$\sigma_V$	DD	$\sigma_D$	HIGH	LOW	TOT.	SO <sub>2</sub>
1	HIGH	279	41	7.0	3.0	26.1	11.7	30	9	39	0.20
W	LOW	256	49	8.8	3.0	12.2	10.0	15	43	58	
2	HIGH	254	37	10.4	3.5	28.2	9.6	26	4	30	0.10
W	LOW	245	41	11.6	4.2	8.2	9.1	8	29	37	
3	HIGH	276	41	8.9	2.4	28.8	10.3	13	2	15	0.20
W	LOW	246	39	9.7	3.8	12.3	11.4	12	40	52	
4	HIGH	268	38	5.8	2.4	26.3	11.5	15	3	18	0.20
W	LOW	262	48	7.7	3.3	15.5	12.3	27	52	79	
1234	HIGH	31	23	7.5	3.9	22.2	9.9	41	17	58	0.05
NE	LOW	45	24	6.8	3.7	16.5	8.5	52	123	175	
1234	HIGH	150	18.7	6.6	3.6	17.5	10.8	24	7	31	0.10
SE	LOW	125	25.2	6.7	2.9	14.5	8.9	32	82	114	

Table 2.16 Discriminant Analysis Hyde Park Tam Station Summer 1966-67

T/S		WD	$\sigma_W$	WV	$\sigma_V$	DD	$\sigma_D$	HIGH	LOW	TOT.	SO <sub>2</sub>
1	HIGH	256	32	4.5	2.0	0.2	0.7	29	17	46	0.10
	W LOW	253	44	5.0	1.9	0.3	1.0	23	48	71	
2	HIGH	249	20	8.1	1.9	0.3	0.5	18	14	32	0.05
	W LOW	249	36	8.5	2.5	0.1	1.5	24	21	45	
3	HIGH	243	30	5.6	2.0	0.07	0.5	36	6	42	0.05
	W LOW	256	43	8.3	2.5	0.24	1.0	13	20	33	
4	HIGH	249	34	3.3	1.4	1.0	2.6	20	5	25	0.10
	W LOW	249	40	5.5	2.2	0.25	0.9	22	66	88	

Table 2.17 Discriminant Analysis Hyde Park Tam Station Fall 1966-67

T/S		WD	$\sigma_W$	WV	$\sigma_V$	DD	$\sigma_D$	HIGH	LOW	TOT.	SO <sub>2</sub>
1	HIGH	267	33	6.5	2.4	21.6	8.9	34	6	40	0.20
W	LOW	256	43	8.3	3.3	11.4	10.7	22	71	93	
2	HIGH	275	51	8.1	3.9	27.9	6.6	14	3	17	0.20
W	LOW	253	40	10.0	3.9	13.6	10.5	28	71	99	
3	HIGH	272	28	7.9	3.2	28.2	5.6	19	0	19	0.20
W	LOW	259	46	9.4	3.7	12.4	10.0	20	66	86	
4	HIGH	258	38	6.7	3.0	21.9	8.1	43	11	54	0.10
W	LOW	253	42	8.5	3.4	9.1	9.5	14	58	72	
1234	HIGH	30	25	3.2	1.2	16.3	11.3	5	1	6	0.10
NE	LOW	36	28	6.1	4.2	7.1	8.6	23	108	131	
1234	HIGH	160	16	5.8	2.0	24.2	8.5	15	2	17	0.20
SE	LOW	140	28	6.0	2.8	9.3	10.8	20	74	94	

Table 2.18 Discriminant Analysis Hyde Park Tam Station Fall-Winter-Spring 1966-67

T/S		WD	$\sigma_w$	WV	$\sigma_v$	DD	$\sigma_D$	HIGH	LOW	TOT.	SO <sub>2</sub>
1234	HIGH	148	40	4.7	2.0	25.0	11.1	16	2	18	0.20
E	LOW	74	56	6.4	4.0	19.7	13.4	34	141	175	

$\text{SO}_2 \geq 0.20$  ppm data points were encountered in these wind sectors.

The results of this series of tests are discussed below.

#### Hyde Park - Winter

As indicated in Table 2.14, wind direction and degree day proved to be fairly effective discriminators for winds in the western hemisphere during all four time periods in the winter season. The significance of the degree day is not surprising in view of the predominance in Hyde Park, of relatively old, coal fired, low-rise residential structures which surround the TAM receptor and tend to impose a fairly typical space heating emission pattern on the area.

It is noteworthy that the standard deviation of wind direction in both the high and low  $\text{SO}_2$  groups tends to be about  $35^\circ$ , while the centroids of the groups are only about  $25^\circ$  apart. The overlap of wind sectors is not surprising in view of the aforementioned local emission distribution pattern, but it is, perhaps, significant that the large industrial and utility complex which lies between about  $270^\circ$  and  $330^\circ$  did not tend to shift the high  $\text{SO}_2$  wind sector centroid further north. This result tends to reinforce the tentative conclusion that Hyde Park is very largely self-polluting.

Wind speed proved to be a rather poor discriminator, as the table indicates. A mean wind speed of about 8.8 mph with a standard deviation of about 3 mph was characteristic of all groups. The difference between centroids was only about one mph, with the higher mean wind speeds

appearing in the low  $\text{SO}_2$  groups, as would be expected. It is evident that, under normal conditions, even during time period 4 (0300 - 0900), the prevailing southwesterly flow during winter is characterized by a fairly steady six hour average wind speed.

In the northeastern quadrant, it is significant that very few high  $\text{SO}_2$  samples are available, even if all four time periods are lumped for a single test run. This result is, of course, due to the low source density in the direction of Lake Michigan, which lies less than one mile east of the Hyde Park receptor. Wind direction and degree day are again significant discriminators, while the mean wind speeds in the high and low  $\text{SO}_2$  groups are almost identical at about 4.4 mph. The small wind speed standard deviation in the high  $\text{SO}_2$  group is probably due to the fact that relatively few data points were available in this group. This fact also accounts for the anomaly that the low  $\text{SO}_2$  group, with a larger wind speed standard deviation, has a lower mean wind speed than has the high  $\text{SO}_2$  group.

In the southeast quadrant, the high  $\text{SO}_2$  mean wind direction is  $167^\circ$  - bearing toward the south Michigan shoreline with its clusters of large, high rise apartments and toward the Gary - Hammond industrial area. Wind speeds in both groups are higher than were encountered in the northeast quadrant, and the significance of degree day as a discriminator is considerably less than for the other wind sectors. The latter result is indicative of the presence of a large but distant industrial concentration which could be expected to be relatively

insensitive to a space heating emission pattern.

A total of 721 data points were evaluated for the Hyde Park winter test series described above. The discriminant analysis technique, applied to the same body of data employed to generate the three variable, linear discriminant equation for each group, yielded a total of 532 correct estimates or a gross score of 74%. The ratio of correct estimates to total data points was essentially the same in each wind sector and time group. Moreover, in the high  $\text{SO}_2$  groups, where correct estimates are of more importance, the score for correct estimates compared to actual cases was also approximately 74%. These results cannot, however, be interpreted as "skill scores" since the probability of random correct guesses was not evaluated.

#### Hyde Park - Spring

The results of the spring (March - April - May) test series shown in Table 2.15 are substantially identical to those of the winter series described above, with several significant exceptions:

- 1) It was necessary, in several cases, to partition the data about a lower  $\text{SO}_2$  threshold than 0.2 ppm, in order to obtain a reasonable sample size in the high  $\text{SO}_2$  group. This is a direct consequence of the reduced space heating emissions and increased natural gas use that are characteristic of this warmer season;
- 2) A definite diurnal wind speed cycle is evident in the western hemisphere, higher winds are prevalent in the afternoon transition period (1500 - 2100) and lower winds are characteristic of the

morning transition period (0300 - 0900).

- 3) Degree day is a particularly effective discriminator, since extreme variations in temperature are greatest during this season.

Essentially the same high  $\text{SO}_2$  wind sectors which appeared in the winter series are indicated in the spring data, however, it is noteworthy that considerably more data was available in the eastern quadrants - as would be expected during spring when lake breezes occur with the greatest frequency.

The gross tally for the spring test series was 518 correct estimates out of a total of 706 data points. This corresponds to a score of 73%, however, the high  $\text{SO}_2$  group scores tended to be better than 75% for all time periods.

#### Hyde Park - Summer

The eastern hemisphere was not investigated for the June - July - August test series, since virtually no  $\text{SO}_2$  concentrations above 0.05 ppm were recorded in this wind sector. In the western hemisphere, as shown in Table 2.16, it was necessary to partition the data at 0.1 ppm in time periods 1 (0900 - 1500) and 4 (0300 - 0900) to obtain an adequate sampling in each group, while in time periods 2 (1500 - 2100) and 3 (2100 - 0300) it was necessary to partition at 0.05 ppm.

These partition thresholds were dictated by the virtual cessation of space heating and city-wide conversion of major dual-fuel utility and industrial plants to dump-rate natural gas. This situation is characteristic of Chicago's summer season. The resultant effect is also

reflected in Table 2.16 by the essential failure of degree day as a discriminator.

Wind direction and speed remain as the significant discriminant variables, but in this case, the mean wind direction tends to vary only slightly between the high and low  $\text{SO}_2$  groups, leaving wind speed as the dominant discriminator. The diurnal wind speed cycle is evident, and the difference between mean winds in time periods 2 and 4 is particularly marked.

The result of the effective loss of two of the more significant discriminators during this season was a notable reduction in the "prediction" score. Out of 382 data points, 258 or 68% were correctly estimated. The score for the high  $\text{SO}_2$  groups is approximately the same as the gross score.

#### Hyde Park - Fall

With the advent of colder weather and the restoration of degree day as an effective discriminator, the discriminant score of the fall series shows an improvement over that of the summer tests. Since a part of the fall season is characterized by warm weather and high natural gas use by industry and the utilities, it was again necessary to partition some of the data groups at a lower  $\text{SO}_2$  concentration than 0.2 ppm in order to provide an adequate sample size in each group.

The results of the fall tests are much the same as those described previously. Wind direction, speed and degree day are all fairly good discriminators in this case, and the effect is manifested as a modest

improvement in the gross score. Out of a total of 728 data points, 578 or 79% were correctly estimated.

#### Hyde Park - Fall, Winter, Spring

Since the eastern hemisphere was characterized by a relative scarcity of  $\text{SO}_2 \geq 0.20$  ppm data, a final test run was made in which all three "heating" seasons, all four time periods and both eastern quadrants were included. The data was partitioned at 0.20 ppm on the premise that the greatly enlarged data inventory would yield a statistically significant sampling in both groups. In fact, only 18 data points were available in the high  $\text{SO}_2$  group, in contrast to 175 in the low  $\text{SO}_2$  group.

As shown in Table 2.18, the mean wind direction associated with high  $\text{SO}_2$  concentrations was  $148^\circ$ , while the low  $\text{SO}_2$  direction was  $74^\circ$  - toward the lake. Wind speed and degree day were both significant discriminators, hence a score of 157 correct estimates out of 193 cases, or 81% was obtained. The high  $\text{SO}_2$  group score was 88%.

#### Lakeview - Summer

A final test series was run for the Lakeview receptor (TAM-2). This series was intended as a trial of the method at a receptor site other than Hyde Park, and was specifically directed toward the identification of the "Northwest" Edison power plant, which bears about  $240^\circ$  at two miles from the Lakeview receptor. Test runs were made in the northwest and southwest quadrants. Data corresponding to the summer season were chosen in order to minimize the effects of space heating on the measured air quality. Since the Northwest plant cannot burn

natural gas, its effluent should have been detected if it reached ground level in the vicinity of the TAM receptor.

The results of this test series are shown in Table 2.19. Wind direction and speed are effective discriminators, and the tally for data partitioned about 0.05 ppm is 235 correct out of 302 cases - a gross score of 78%. No evidence of the operation of the "Northwest" power plant was apparent, in fact, the low SO<sub>2</sub> mean wind direction was more nearly consistent with the bearing of the Northwest plant than was the high SO<sub>2</sub> group wind. The explanation of this failure to identify the effects of the Northwest plant very likely lies in the fact that the plant and TAM receptor are fairly nearby, so that the stack effluent may not reach the ground in time to be detected. The fact that this plant is one of the older, smaller and less efficient power stations causes it to be put on-line somewhat less frequently than other Edison plants - hence the sampling of days which included Northwest emissions may have been relatively small.

### 3 Validation

The results reported in the preceding discussion were, as indicated, obtained by using the discriminant predictor equations generated in each test run on the same data sets employed to generate the predictor equations. The reported "predictive" accuracy scores cannot, therefore, be regarded as a true validation of the methodology, despite the rather impressive gross score for all test runs of 2278 correct estimates out of 3032 trials - corresponding to a mean "prediction" accuracy of

Table 2.19 Discriminant Analysis Lakeview Tam Station Summer 1966-67

T/S		WD	$\sigma_w$	WV	$\sigma_v$	DD	$\sigma_D$	HIGH	LOW	TOT.	SO <sub>2</sub>
1234 NW	HIGH	287	18	4.8	2.4	0.3	1.4	13	3	16	0.05
	LOW	300	22	7.9	2.8	0.6	0.9	25	64	89	
1234 SW	HIGH	213	18	7.0	3.1	1.0	2.7	15	7	22	0.05
	LOW	237	21	8.2	3.3	0.0	0.4	32	143	175	

75% for all seasons. The minimum score of 68% was obtained in the summer - Hyde Park test and the maximum score of 81% was achieved for the summer - Lakeview test.

A true validation of the methodology requires that the predictor equations be applied to a body of data not used to generate them. Air quality data for the winter months of 1968 has only recently become available at Argonne, hence the attempt to validate the predictor equations generated with 1966-67 data was in its initial stages at the time that this document was prepared.

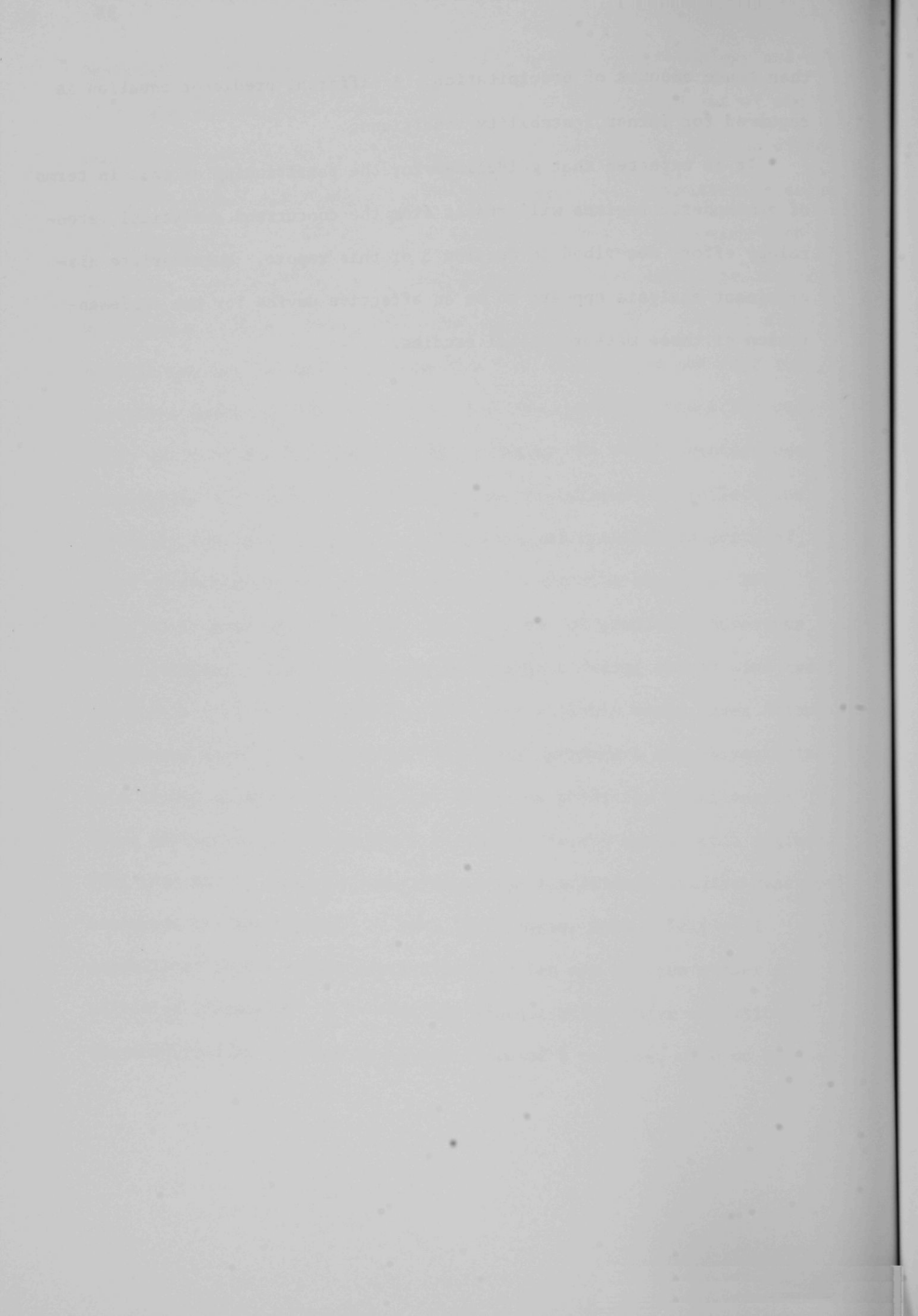
Although the validation sample thus far available is not large enough to be statistically significant, the prediction score developed to date is consistent with the results reported in the previous discussion. Forty sample days, extending from January through March of 1968, were employed for the initial validation of the time period 1 (0900 - 1500) predictor equations. The only restriction imposed in selecting this validation sample was that days with more than trace quantities of precipitation were excluded. A total of 34 correct estimates in the 40 day data sample were achieved. Of the six errors, two were within 0.01 ppm and three were within 0.05 ppm of the partition threshold of 0.20 ppm.

A limited effort to extend the validation described above will be made during the forthcoming quarter, but an extensive validation of the results of these essentially exploratory predictor equations is not warranted. The study reported here was, it will be recalled,

designed to evaluate the potential of an analytical methodology and not to produce a prediction model. Indeed, it would be quite out of the question to expect that a prediction system based solely on wind direction, wind speed and ambient temperature could yield consistently accurate forecasts. The omission of a critical diffusion parameter such as mixing layer depth would virtually guarantee that such a predictor model would have an unacceptably high rate of failure. Even if all significant discriminant variables had been included in the test runs described above, it does not follow that the resultant predictor equations would be universally applicable, unless the data inventory used to generate the predictor model were also partitioned to reflect the differing atmospheric stability situations and circulation patterns which characterize various meteorological pollution regimes. For example, it does not follow that the same set of predictor equations which generate reliable and accurate forecasts during steady wind speed conditions will be effective for light and variable winds under strong subsidence inversion conditions. The same parameters may characterize both states of the atmosphere, but different predictor equations in these parameters may be required for the different atmospheric regimes. That this is the case, is evidenced by the statistical studies described elsewhere in this report. It has, for example, been fairly well established that a single regression equation can provide rather good validated "forecasts" of ambient  $\text{SO}_2$  concentration under conditions characterized by a Turner stability class of 4 or less, with no more

than trace amounts of precipitation. A different predictor equation is required for Turner 5 stability conditions.

It is expected that guidelines for the partitioning of data in terms of atmospheric regimes will result from the concurrent analytical meteorology effort described in Section 3 of this report. Multivariate discriminant analysis appears to be an effective device for the implementation of these meteorological studies.



## CHICAGO AIR POLLUTION DISPERSION MODEL

### 3.0 Meteorology

J. Carson  
D. Gatz  
H. Moses

### 3.0 Meteorology

#### 3.1 Meteorological Data Acquisition

The meteorological data collected at the Argonne site have been added to the master data file. These data include hourly values of wind speed at 3 altitudes, wind direction at two levels, air temperature, dew point, relative humidity, solar radiation, net radiation, air pressure, precipitation, and lapse rate.

The surface weather data from the four area airports (O'Hare, Meigs, Midway, and Glenview) as well as two full years of TAM data have been incorporated into the master file.

Listings of 19 months of rawinsonde data from the two nearest Weather Bureau Stations (Peoria, Illinois and Green Bay, Wisconsin) are being made. These data include significant and mandatory levels from the surface through the 700 millibar level. Computer procedures to plot these soundings and to compute hourly mixing depths are being developed.

#### 3.2 Experimental Studies

Progress has been made in implementing the meteorological experiments discussed in the previous Quarterly Reports.

##### 3.2.1 Instrumenting Buildings

DAPC has ordered the radiation shields and temperature sensors for the Hancock Building. Construction of the building itself is continuing, and it will be 6 to 12 months before the sensors can be mounted and data collection begun.

### 3.2.2 Helicopter Program

The DAPC has ordered the flight package from SIGN-X Laboratories, Essex, Conn.; delivery is expected in November 1968. Similar equipment is being used by East in Montreal, Davidson in New York City and Carpenter of T.V.A. They indicate that the equipment is rugged and operates satisfactorily.

Air temperature, dew point, pressure altitude and  $\text{SO}_2$  concentration are measured continuously and recorded on two charts using four pens. Funds to digitize the system are not now available, but the recorders can be modified to accept encoders without major changes.

The Chicago Fire Department will fly the package and provide the pilot. DAPC will supply a technician to fly with the instrument and make such recordings as are necessary to evaluate the data, such as location, cloud information, flight speed, etc.

Argonne's role in this experimental project is to design and operate the flight program so that maximum information concerning pollution and diffusion over the city can be obtained per flight. This includes the scheduling and routing of individual flights based in part on the weather forecast. A frequency of one flight or less per week is expected. Argonne will also be required to analyze the resulting data. The flight program will be modified as more is learned about atmospheric conditions over the city. No changes in the flight patterns outlined in the previous report are now suggested.

### 3.2.3 Tracer Studies

Sulfur hexafluoride ( $\text{SF}_6$ ) will be used to measure air flow and dilution rates in the city.

The analysis system developed by the National Air Pollution Central Administration (NAPCA) in Cincinnati for this tracer gas will be used. (12,13) The ultrasensitive detectability of this material results from the high response characteristics of electron capture detectors to halogenated materials. Much of the experimental work to date has been to optimize procedures so that very high sensitivities can be realized. The gas will be released at a rate of about 3.5 gm/sec or 1 cfm and will be collected in plastic bags using samplers borrowed from NAPCA. These samplers contain a small battery-driven pump which fill 20-liter bags at a rate of about 120 ml/minute.

The Argonne Industrial Hygiene and Safety Division has modified their gas chromatograph to determine concentrations of this tracer material. A Model GC 1500 Micro-Tek unit is being used.

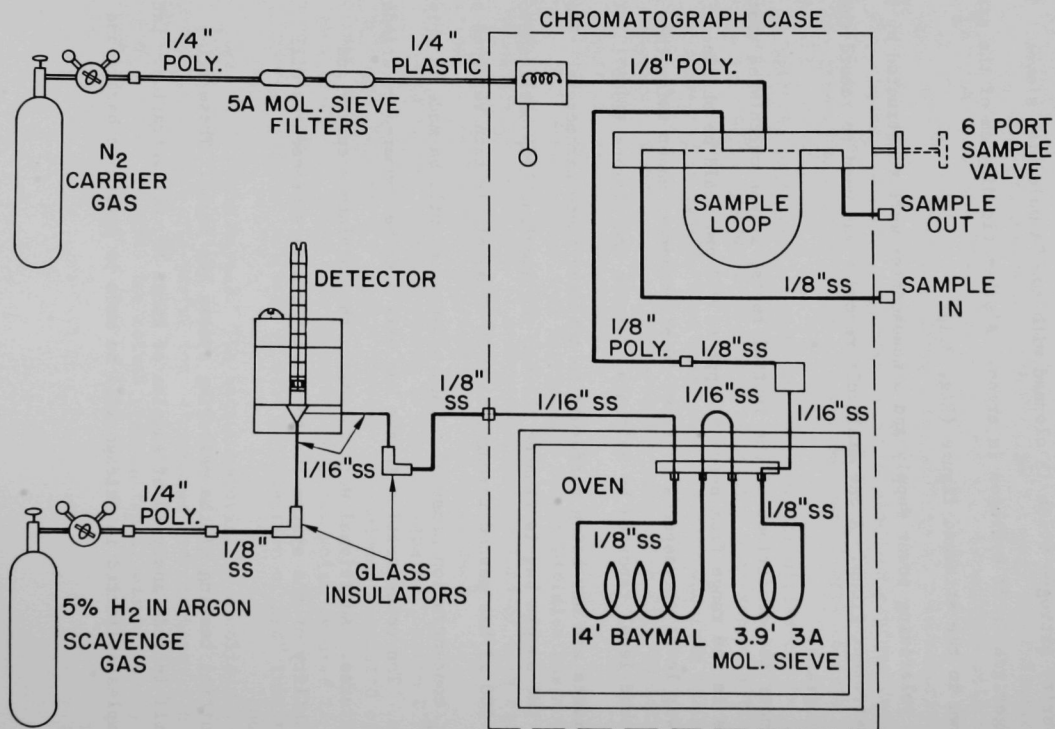
The system initially chosen is that designated "System B" by Saltzman, Coleman and Clemons (1966). The columns consisted of a 3.9 foot section of 40-60 mesh 3A molecular sieve which is used to remove interfering water, followed by a 14 foot section of 1/8" tubing containing 40-60 mesh Baymal. The latter material is a colloidal alumina which is particularly useful for halogenated hydrocarbons. In order to obtain enough material for column preparation it was necessary to sieve several pounds.

The standard inlet in the chromatograph was replaced with a 7-port valve containing a 0.25 ml sample loop. The carrier gas to be used is high purity nitrogen which is cleaned with two 5A molecular sieves. The scavenger gas is 5% hydrogen in argon. A schematic diagram of the system is shown in the attached figure (Fig. 3.1).

A polarizing power supply and a nanoammeter were constructed by the IHS instrument group. A one millivolt recorder was used to record the chromatograms.

Under the conditions of the initial tests, it was calculated that samples in the range from about 0.2 ppb to 0.2 ppm would be obtained. The lower level corresponds to about 20 picoamperes, about twice the background level reported by Saltzman, Coleman and Clemons (1966). Experiments are now being performed to optimize these parameters. The air in the sample bag is flushed through the sampling loop until approximately 100 ml has passed through. A 0.25 ml sample is then retained and the  $\text{SF}_6$  concentration measured. Each measurement will be made in triplicate. The concentration in the bag will also be compared to standard gas mixtures. Additional work to insure the absolute accuracy and repeatability of the system and to develop analysis procedures will continue.

Initial testing of the measuring system has begun. These trial runs will include analysis of samples of known  $\text{SF}_6$  concentration. Later, air samples collected in Chicago will be made to determine background levels.



112-9763

Fig. 3.1 Schematic Diagram of Chromatographic System for  $\text{SF}_6$  Analysis

### 3.2.4 Second Air Pollution Control Tests

The second in a series of fuel-switch test programs was conducted from 16 June through 4 July 1968. This "simulation inversion" trial run was planned in cooperation with Chicago Department of Air Pollution Control personnel. The test had dual primary objectives--to act as a dress rehearsal for implementing an effective SO<sub>2</sub> abatement procedure during a forecast period of pollution buildup and to provide Argonne with detailed air quality, meteorological and SO<sub>2</sub> emission data for use in developing the diffusion model. If possible, the fuel switches were to have been made during periods of nearly constant diffusion conditions so that the effect of various SO<sub>2</sub> sources could be isolated.

DAPC officials prepared and sent letters to the major SO<sub>2</sub> emitters in the city, outlining the test program and asking for their cooperation. Forms to record hourly fuel consumption and other factors were prepared and sent to 79 industrial, commercial, residential and utility power plants.

The response to this request was moderately favorable: all six of the Commonwealth Edison plants, 24 of 50 dual-fuel and 19 of 23 single-fuel plants agreed to participate. Follow-up calls were made to insure cooperation of the boiler plant engineers.

During the test period (mid-summer), space heating, with its unmeasured and highly variable SO<sub>2</sub> emission rates, would be at a minimum. DAPC's previous experience indicated that most plants with dual-fuel capability would be using gas, and that the cost of switching to

and from high sulfur fuel would be minimized.

Those industries with single-fuel capacity (coal or oil) were asked to retain and submit to DAPC detailed hourly fuel consumption data from 16 June through 6 July 1968. Plants with dual-fuel capacity were also asked to maintain hourly fuel use records for the same period. They were further requested to burn their usual fuel for that season during the first week of the test, and convert to maximum high sulfur fuel between 0700 and 1100 CST on both 24 June and 1 July 1968.

During the week of 23 June, Commonwealth Edison was to convert their plants to maximum gas after 24, 48, or 72 hours, with industry converting to maximum gas 1 day later. The exact date of the fuel switch for the power plants was to be based on special weather forecasts prepared by the Chicago U.S. Weather Bureau office. It was hoped that steady weather conditions (same wind speed and direction, no rain, etc.) would prevail for 48 hours or more, so that the observed  $\text{SO}_2$  concentrations at each of eight TAM stations could be compared with days of similar weather but different  $\text{SO}_2$  emission patterns.

Again on 1 July, all plants with dual-fuel capacity were asked to convert to maximum sulfur content coal or oil. During this week, industry was asked to convert back to minimum sulfur fuel on a date selected on the basis of the weather forecast, with the Edison Company following one day later.

### Implementation of the Test

Weather conditions during the week of June 23rd were most unfavorable, with numerous periods of rain and strong and variable winds. The winds were forecasted to be strong easterly on 26 and 27 June. These factors, plus a shortage of coal in some plants, caused cancellation of the test for that week, and little useful data was obtained.

Weather conditions for the final week of the test were more favorable. Based on an accurate forecast, industry converted to gas after 24 hours and the power plants one day later, on July 3rd.

During and following the switches from low sulfur fuel to coal and/or oil and return, Chicago was in a westerly to northwesterly flow of cool air behind a strong (for the season) cold front. The low pressure center associated with this front was over Sioux City, Iowa on Sunday morning, June 30th, the day before the test started. This low pressure center moved to the north and then northeast, with the cold front crossing the city between 2200 and 2400 CST on the 30th. Light thunderstorms accompanied the frontal passage, with 0.09 in. of rain falling at Argonne, 0.04 in. at Midway.

At Argonne, strong (15-25 knots) SW surface winds were observed prior to the arrival of the cold front. The winds switched to moderate (10-15 knots) NW for about 6 hours while the frontal zone passed. They backed to W for the remainder of the night and the daylight hours on Monday, then veered to moderate NW to N flow until 1400 CST on July 3rd. Wind speeds decreased as the center of the cold polar high pressure area

moved from WNW to ESE on a path south of Chicago. The Argonne wind direction backed to W and SW and remained there through July 4th. Except on July 3rd, when a lake-breeze circulation covered all of Chicago but did not reach Argonne, the TAM wind reports were basically similar.

The strength of the front and the cold air mass are shown by the departures from normal temperatures at Midway Airport: June 30th, before the cold front arrived, was 9°F above normal; July 1st, 1°F above; July 2nd, and 3rd both 11°F below; and July 4th, 7°F below. These cool maximum temperatures (71°F on the 2nd, 75°F on the 3rd) would indicate that electrical power requirements for air conditioning were at a minimum.

A complete analysis of this fuel switch test must await the processing of the actual SO<sub>2</sub> emissions by DAPC personnel. Since the return of emission data, by participating fuel users, tends to be a slow and sporadic process, this effort has served to pace the analysis.

Hourly mixing depth and 6-hourly gradient wind data for Chicago have been developed and will be used in the assessment of the test results. For this analysis, the wind and SO<sub>2</sub> values used are those observed every 15 minutes, rather than averages over 1 hour as in the case of the data employed in the development of the diffusion model.

#### Air Quality and Meteorological History

On Sunday June 30th, when most boilers were idle or on gas, SO<sub>2</sub> levels at all TAM stations were very low ( $\leq 0.05$  ppm) until 1800 CST, when values  $\geq 0.10$  ppm were observed at TAM 2, 6 and 7. All SO<sub>2</sub> values

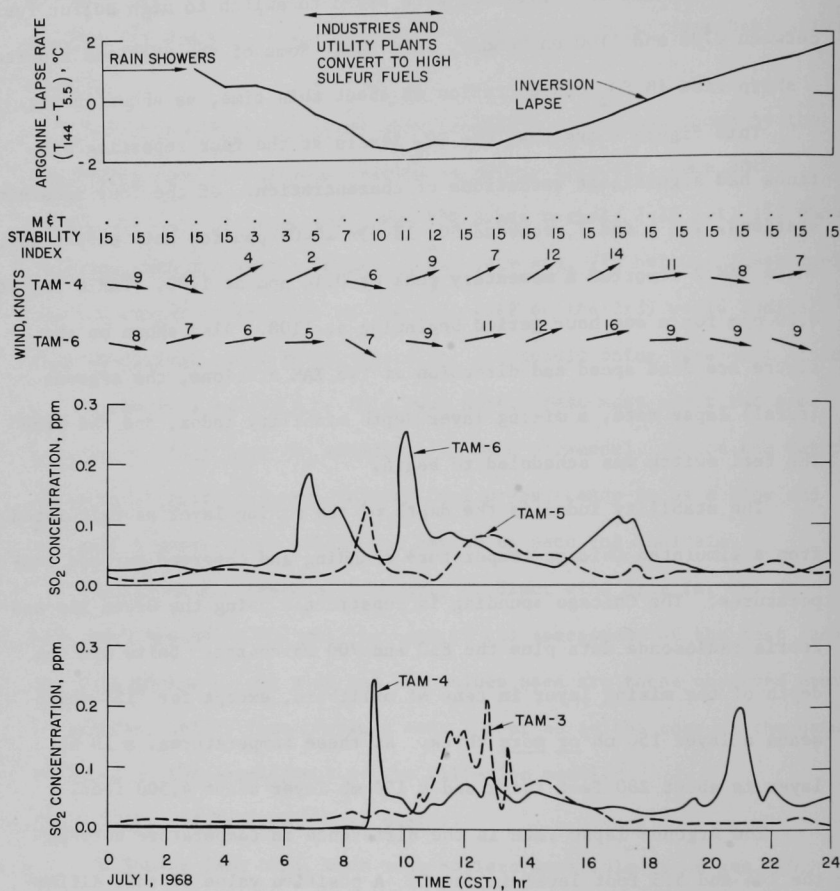
dropped to near zero by 2300 CST, when the fresh polar air mass moved into the City.

Industry and the utilities were asked to switch to high sulfur fuel between 0700 and 1100 on Monday, July 1st. Some of the stations reported a sharp rise in  $\text{SO}_2$  concentration at about this time, as shown in Fig. 3.2.

This figure shows that the  $\text{SO}_2$  levels at the four reporting stations had significant variations of concentration. Of the four remaining stations, TAM 1 and 7 recorded  $\text{SO}_2$  levels  $\leq 0.04$  ppm for this entire day, while TAM 2 reported a momentary peak of 0.14 ppm at 1700. TAM 8 reported 0.10 ppm for a one hour period beginning at 1100. Also shown on the figure are wind speed and direction at two TAM stations, the Argonne (rural) lapse rate, a mixing layer depth stability index, and the time the fuel switch was scheduled to begin.

The stability index is the depth of the mixing layer as calculated from a simulated Chicago temperature sounding and observed surface temperatures. The Chicago sounding is constructed using the Green Bay and Peoria radiosonde data plus the 850 and 700 mb charts. Units are the depth of the mixing layer in tens of millibars, except for "15" which means a layer 150 mb or more thick. At these temperatures, a 10 mb layer is about 280 feet thick and a 150 mb layer about 4,500 feet.

The Argonne lapse rate is the difference in temperature between the 144 and 5.5 foot level in deg C. A positive value of this difference indicates an inversion (stable); the dry adiabatic or neutral lapse rate for this layer is  $-0.42^\circ\text{C}$ .



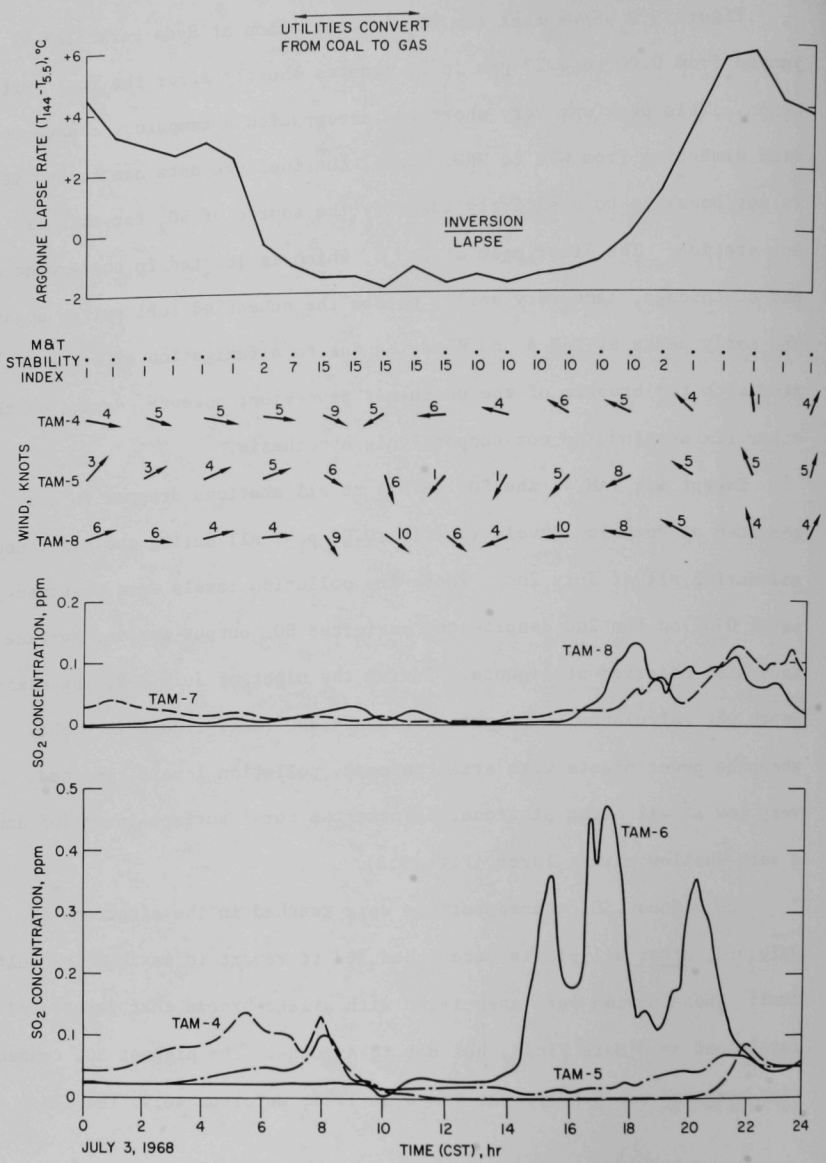
112-9764

Fig. 3.2 Time Section of SO<sub>2</sub> Concentrations and Wind Velocities at Selected Tam Stations, Rural (Argonne) Lapse Rate, Stability Index and Period of Precipitation

Figure 3.2 shows that the  $\text{SO}_2$  concentration at Hyde Park (TAM 4) jumped from 0.00 to 0.23 ppm in 15 minutes shortly after the fuel switch began. This peak was very short and accompanied a temporary change in wind direction from WSW to WNW. Until the fuel use data are ready, it is not possible to positively identify the source of  $\text{SO}_2$  for this or any station. The first peak at TAM 6, which is located in the southern end of Chicago, came very early, before the scheduled fuel switch began. The early peaks at TAM 4 and 6 may be due to a fumigation effect associated with the breakup of the nocturnal inversion; however, data from the other six stations do not support this hypothesis.

Except for TAM 4, the  $\text{SO}_2$  levels at all stations dropped to and remained at very low levels (mostly  $\leq 0.03$  ppm) all during the night hours and during all of July 2nd. These low pollution levels were observed until 0700 on the 2nd despite the maximized  $\text{SO}_2$  output and the surface inversion observed at Argonne. During the night of July 1-2, the mixing depth was calculated to be greater than 4,500 feet. The next night, when the power plants were still on coal, pollution levels remained very low at all eight stations, despite the rural surface inversion and a very shallow mixing layer (Fig. 3.3).

The highest  $\text{SO}_2$  concentrations were reached in the afternoon of July 3rd, after all plants were scheduled to revert to maximum low sulfur fuel. These maxima were associated with a lake-breeze that penetrated as far inland as O'Hare Field, but not to Argonne. The highest  $\text{SO}_2$  concentration measured was 0.47 ppm at TAM 6 at 1715; unfortunately, the TAM 6



112-9765

Fig. 3.3 Time Section of SO<sub>2</sub> Concentrations and Wind Velocities at Selected Tam Stations, Rural (Argonne) Lapse Rate, Stability Index

wind direction sensor failed to operate properly at this time and this significant item of information is missing. Streamline analyses indicate the missing wind directions are quite similar to those of TAM 5 and 8.

Figure 3.3 shows the time variations of  $\text{SO}_2$  for five stations and wind velocity data for three stations. Also given are the calculated urban mixing depths and the Argonne lapse rate data. The time of the scheduled fuel switch to maximum gas for the Commonwealth Edison plants is shown.

$\text{SO}_2$  concentrations at TAM 1, 2 and 3 were  $\leq 0.04$  ppm until 2200 on July 3rd. Very low concentrations ( $\leq 0.04$  ppm) were observed at seven of the eight TAM stations (all except TAM 4) during the nighttime hours of July 2-3, despite a very shallow mixing depth (280 feet or less), low wind speeds and maximum  $\text{SO}_2$  output from the utilities. The morning  $\text{SO}_2$  at TAM 4 and 5 may be from the Ridgeland and Crawford power plants.

The wind data at the TAM and airport stations show that the lake breeze was well established at the shore line by 0900;  $\text{SO}_2$  concentrations in the air coming into the city from over the lake were very low for the duration of this wind flow.

An analysis of the data at the inland stations (TAM 1, 5, 7 and 8) does not reveal any buildup of  $\text{SO}_2$  along the zone of convergence ahead of the lake breeze front. Stations 5, 7 and 8 show some buildup late in the day, as the lake breeze weakens and disappears.

The most interesting feature of the entire test period is the  $\text{SO}_2$  buildup at Fenger High School (TAM 6). In one hour, the  $\text{SO}_2$  level went from 0.07 to 0.36 ppm.

Large variations in  $\text{SO}_2$  were recorded between 1400 and 2200. An analysis of the wind data from the other stations indicates that the buildup began some time after the winds became easterly. A map of major point sources upwind of this station reveals one about 1.5 miles upwind: the Sherwin Williams Paint Company; however this plant was on 100% gas during this period. Also upwind of the station are many large  $\text{SO}_2$  sources sited along the Calumet River and the Gary-Hammond industrial area. Emission data reduction for these sources is not yet complete; however most of these plants are single-fuel plants using coal and may therefore be suspect.

Commonwealth Edison emission data for this period indicate that the Calumet power plant burned four tons of coal per hour between 0800 and 1200 CST, while the State Line power plant used an average of 289 tons of 3.38% sulfur coal per hour from 1200 to 2300 CST on this date. The State Line plant could be the major source of the  $\text{SO}_2$  observed at TAM 6; however, the observed effect could also be due to emission from the Gary-Hammond industrial area.

The following day, July 4, was a legal holiday with minimum industrial activity. Moderate SW flow covered the city.  $\text{SO}_2$  values  $\geq 0.20$  were observed at TAM 6 at 0500 and again at 2230 and at TAM 8 at 0900. Both of these stations were upwind of the major  $\text{SO}_2$  producers within

the city. These peaks are probably associated with sources outside the City of Chicago.

## Analytical Meteorology

### Summary

The effort during this quarter was characterized by a modification of our original methodology for pollution regime identification. Increased emphasis was placed on letting the data indicate which regimes are necessary to describe Chicago weather for pollution prediction purposes. This represents a somewhat more pragmatic approach than the scheme described in ANL-ES-CC-002, where we proposed to start with a list of possible regimes and seek data that appeared to fit. It appears that statistical studies of very broad data groups, perhaps limited only by season, are more likely to reveal significant pollution prediction parameters. Those points which lie far from regression line will be examined in detail. If similarities are found in the weather situation for groups of apparently anomalous points, this may suggest weather regimes that should be considered separately from the rest of the data. For example, we might find that lower-than-average concentrations at TAM 4 (near the lake front) are often associated with lake breeze situations. This would indicate that the lake breeze should have its own regression equations; i.e. it is a distinct air pollution regime.

To test this general approach, we analyzed the results of nine sample regressions. This analysis is described in detail in Section 3.3.1. One of the conclusions of this study was that winds measured at

the TAM station should be used in regressions for that station. That is, TAM winds are preferable to Midway Airport winds in the equations.

This result is somewhat surprising in view of the discrepancies between Midway and TAM winds that have been found and that were reported in preliminary form at the July Review Committee Meeting. This study is now complete and forms Section 3.3.2 of this report. One of the main conclusions of this section is that TAM winds, despite certain deficiencies are adequate for our work. The usefulness of the TAM winds is demonstrated in the next section (3.3.3), where they are employed to describe the surface wind field in Chicago during a pollution incident.

The modified approach to regime identification involves increased emphasis on the in-depth study of individual cases. It is necessary to determine why the recorded pollution levels were different from the temperature dependent baseline average in these cases. Thus, we were led to examine the 19-20 January 1966 episode, in which  $\text{SO}_2$  concentrations greater than 1.0 ppm occurred at TAM 4. The results of this study appear in Section 3.3.3.

Other types of incidents also require study. For example, it is necessary to determine whether there are certain weather patterns that are associated with local (i.e. one-station) and city wide pollution incidents. To accomplish this, it is necessary to identify those cases of interest. A preliminary report on a procedure to achieve this is provided in Section 3.3.4.

### 3.3.1 SO<sub>2</sub> Regression Upon Temperature: Meteorological Analysis of Anomalous Data Points

A series of statistical regression runs for TAM 4 SO<sub>2</sub> vs. Midway temperature were performed. The results of this series are reported in Section 2 of this report. They suggest that local space heating is the dominant factor in TAM 4 air pollution. They also provided an opportunity to test the modified approach to regime identification through an analysis of apparently anomalous data points.

Those points which lay 0.10 ppm or more off of the baseline temperature regression line were chosen for study. Nine different regressions of TAM 4 SO<sub>2</sub> vs. Midway temperature were made. All computer runs searched on the hours of 0800 - 1300 CST for sunny (total cloud  $\leq 0.8$ ) winter days (1 January 1966--28 March 1966, 1 November 1966--28 March 1967). Thus the program searched 1410 hours on 235 days. The nine search runs returned data points in four wind direction bands and two wind speed bands as follows:

<u>Run No.</u>	<u>Wind Direction (degrees)*</u>	<u>Wind Speed (kt)*</u>
1	315 - 345	9 - 13
2	315 - 345	6 - 9
3	270 - 315	6 - 9
4	270 - 315	9 - 13
5*	270 - 315	9 - 13
6	225 - 270	9 - 13
7	225 - 270	6 - 9
8	180 - 270	6 - 9
9	180 - 270	9 - 13

---

\* Wind at Midway, except run 5, in which the bandwidth criteria had to be met at both Midway and TAM 4.

The nine runs selected 336 data points. Some individual hours were counted more than once because they were selected by two or more runs.

Of the data points selected, 223 (66%) were within  $\pm 0.10$  ppm of the temperature-dependent regression lines for the respective runs. The remainder, 113 (34%), were anomalously high or low. Of these 42 were high, 71 low. Figure 3.4 shows the frequency distribution of deviations from the regression line.

Anomalous values occurred on 48 days;

20 days had high values,

28 had low,

25 days had only one anomalous hour,

23 had more than one.

On the 25 days with one anomalous hour;

11 hours were high,

14 were low

On the 23 days with more than one anomalous hour;

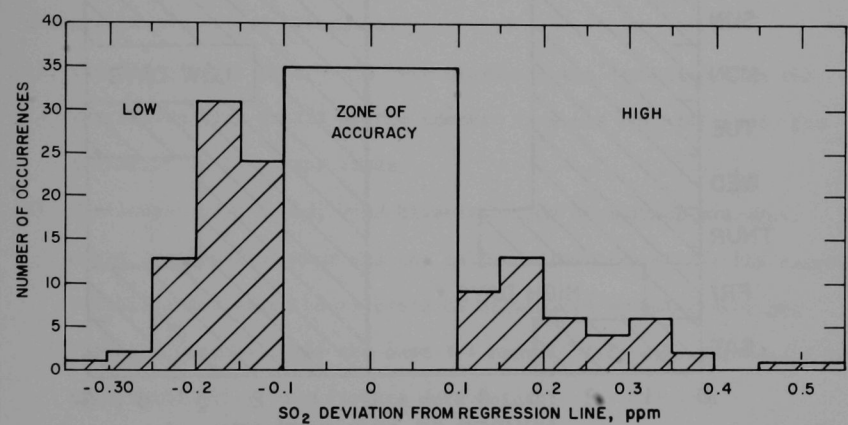
9 days had all high values,

14 had all low,

31 hours were high,

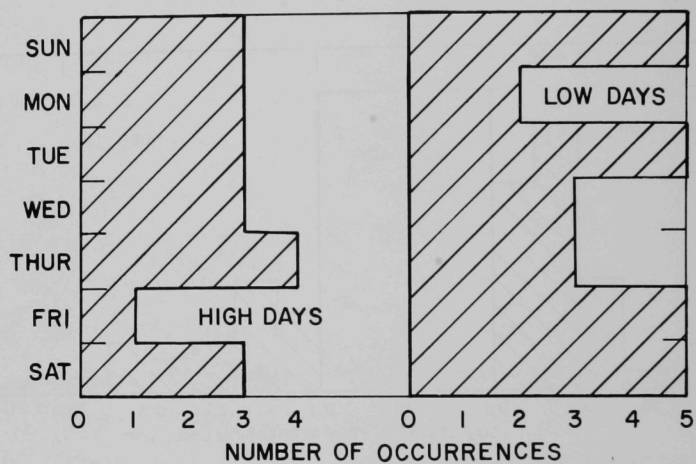
57 low.

No days were found that had both high and low values--a day was either high or low. Figure 3.5 shows the distribution of high and low days by day of the week. There was little preference of either high or low values for any day of the week; the sample is small, however.



112-9766

Fig. 3.4 Frequency Distribution of Deviations from Temperature Regression Lines



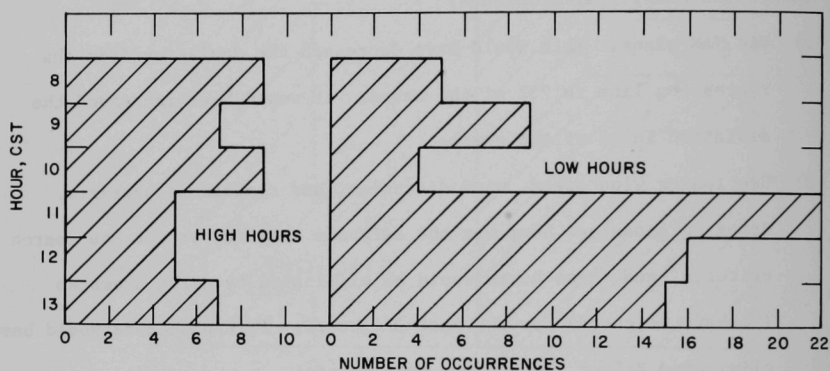
112-9767

Fig. 3.5 Distribution of High and Low Days by Day of the Week

Figure 3.6 shows the distribution of high and low hours by hour of the day. There was perhaps a slight tendency for high points to occur at hours 8, 9 and 10. Low points definitely preferred hours 11, 12 and 13.

The meteorology of each high and low point was subjected to detailed study. No apparent explanation was found for the deviations in 15% of the cases. Inclusion of incorrect values in the  $\text{SO}_2$  averages caused 5% of the deviations. The rest of the cases suggest the following changes in analytical procedure:

- 1) Use TAM winds. This would have decreased the deviation from the regression line in 23% of the cases. It would have increased the deviation in 4% of the cases;
- 2) Use longer wind speed, wind direction, and cloudiness averages. Often an anomalous hour was the only one that day to fit the search criteria, and these hours could be eliminated by using averages (perhaps weighted) for the past 3-4 hours. This procedure would have eliminated 24% of the deviate data points;
- 3) Consider holidays separately. Christmas and the day after (a Monday holiday) were anomalously low in 1966;
- 4) Consider the hours before breakup of the nocturnal inversion separately from the hours after breakup. The hours of 8-13 CST were included in this study, and it was found that high values were often associated with the morning  $\text{SO}_2$  peak which occurs between 7 and 10 CST.



112-9768

Fig. 3.6 Distribution of High and Low Hours by Hour of the Day

The recommendation to use TAM winds is somewhat surprising in view of the discrepancies between Midway and TAM winds which were reported at the July 1968 Review Committee Meeting. That study is now complete and is reported in the next section, together with an explanation of the apparent paradox.

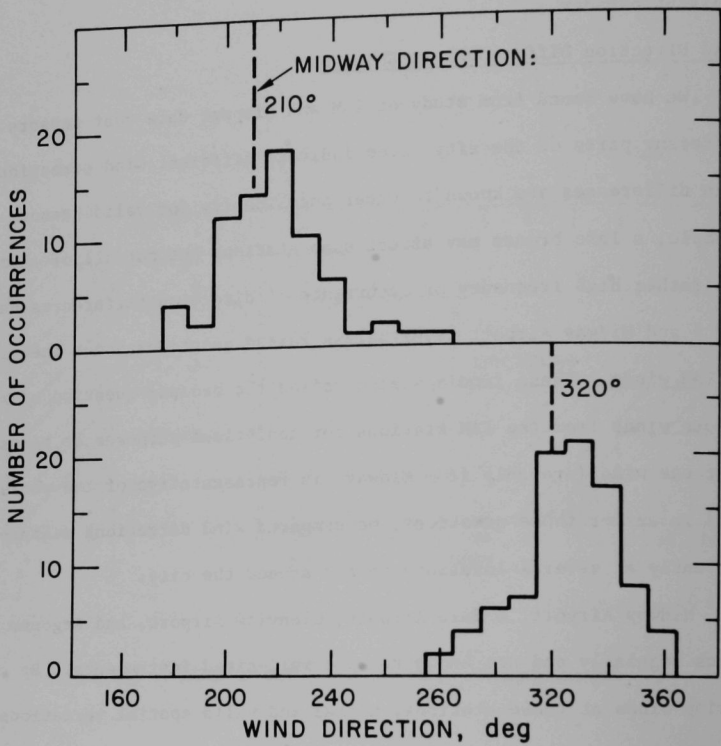
### 3.3.2 Wind Direction Differences in Chicago

We have found from study of TAM and airport data that sensors in different parts of the city often indicate different wind directions. Such differences are known to occur occasionally for valid reasons. For example, a lake breeze may affect some stations but not all of them. The rather high frequency of occurrence of direction differences between TAM 4 and Midway Airport nevertheless raised questions about the validity of TAM winds. These findings also raised the broader question of whether to use winds from the TAM stations for analytical purposes or to assume that one wind (probably from Midway) is representative of the whole city.

To answer these questions, we compared wind directions measured concurrently at several locations in and around the city.

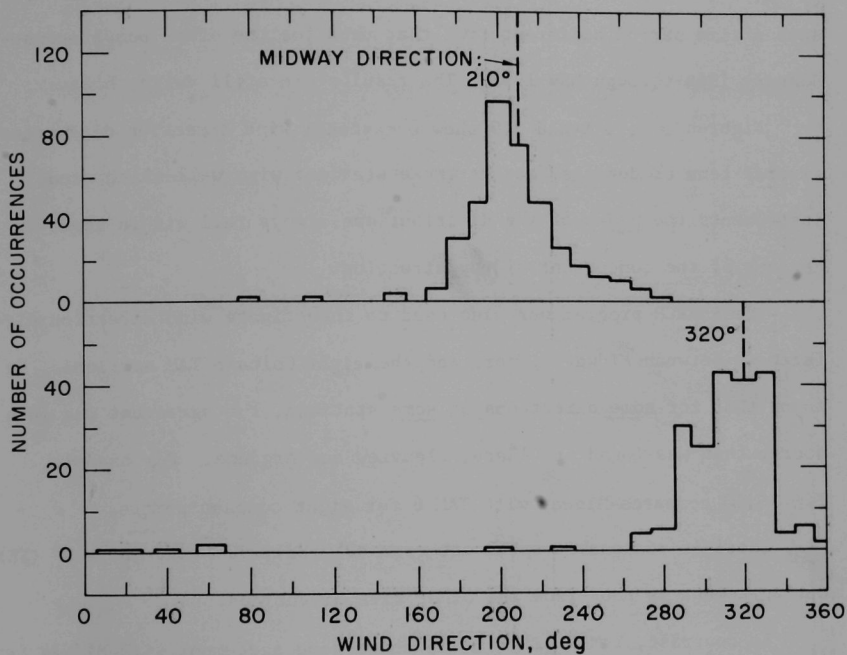
Midway Airport, O'Hare Airport, Glenview Airport, and Argonne record winds regularly and are known to have well-sited instruments. By comparing winds at these stations, normal and valid spatial variations in the wind field should be evident.

The SEARCH program found all hours of Midway from selected directions and printed out wind directions for O'Hare and Glenview for those hours. The frequency distributions shown in Figs. 3.7 (O'Hare) and 3.8



112-9769

Fig. 3.7 Distribution of Wind Direction at O'Hare for Specified Midway Winds



112-9770

Fig. 3.8 Distribution of Wind Direction at Glenview for Specified Midway Winds

(Glenview) were then constructed. (The Midway directions  $210^{\circ}$  and  $315^{\circ}$  were chosen so the distributions could be compared with those for TAM 4, which had been plotted previously.)

Argonne wind direction distributions for selected Midway wind directions are shown in Fig. 3.9. These distributions were computed previously by Moses and Bogner<sup>(14)</sup> for the years 1950-1964. Therefore, they represent a time period different from that used for the other comparisons--January 1966 through May 1967. The results are still valid, however.

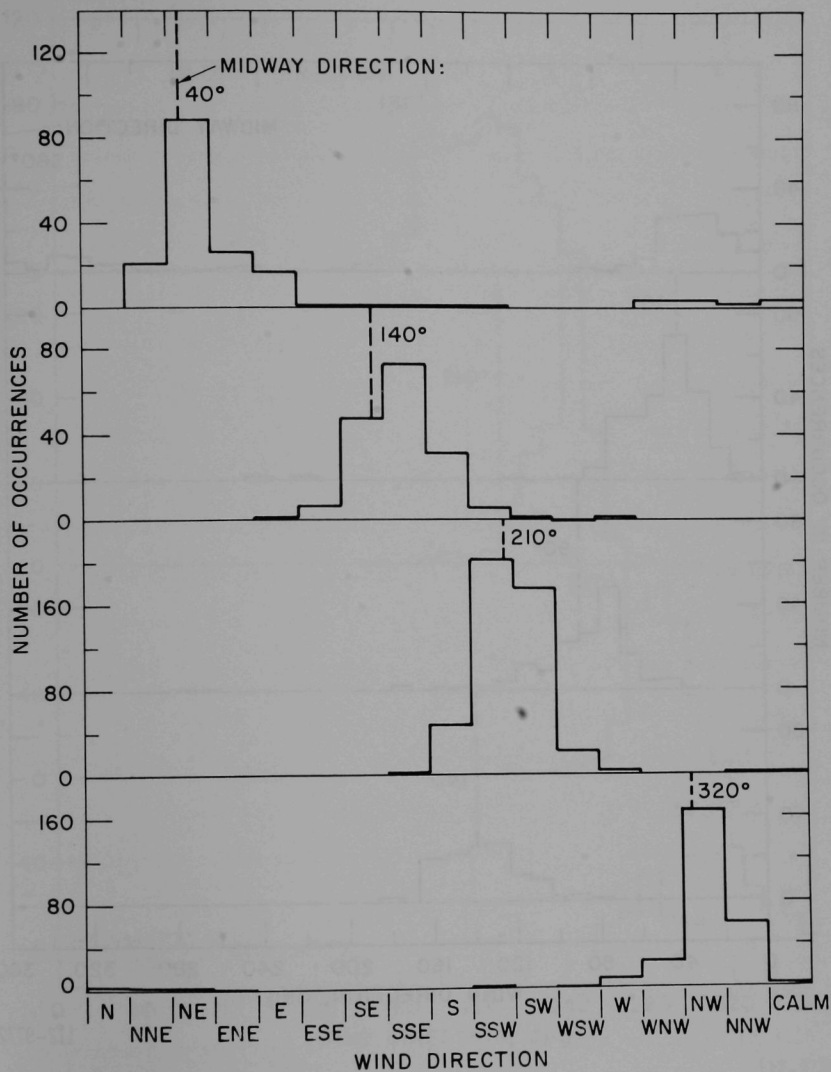
Figures 3.7, 3.8 and 3.9 show occasional wind direction differences of several tens of degrees, but at these stations with well-sited wind instruments the peaks of the distributions always fall within about 10 degrees of the concurrent Midway direction.

The SEARCH program was also used to investigate wind direction differences between Midway Airport and the eight Chicago TAM stations. We found that for some directions at some stations, the agreement was much poorer than was found at O'Hare, Glenview and Argonne. For example, Fig. 3.10 compares Midway with TAM 6 for eight compass points.

There is reasonable agreement from  $40^{\circ}$  (NE),  $90^{\circ}$  (E), and  $140^{\circ}$  (SE), but agreement is poor from the other five directions.

In contrast, TAM 7 (Fig. 3.11) shows good agreement with Midway from all eight directions studied.

Not all directions at TAM 6 are affected, so the problem there does not appear to be aerovane miscalibration, which would affect all directions in the same way. Furthermore, no evidence of seasonal or



112-9771

Fig. 3.9 Distribution of Wind Direction at Argonne for Specified Midway Winds

(Glenview) were then constructed. (The Midway directions  $210^{\circ}$  and  $315^{\circ}$  were chosen so the distributions could be compared with those for TAM 4, which had been plotted previously.)

Argonne wind direction distributions for selected Midway wind directions are shown in Fig. 3.9. These distributions were computed previously by Moses and Bogner<sup>(14)</sup> for the years 1950-1964. Therefore, they represent a time period different from that used for the other comparisons--January 1966 through May 1967. The results are still valid, however.

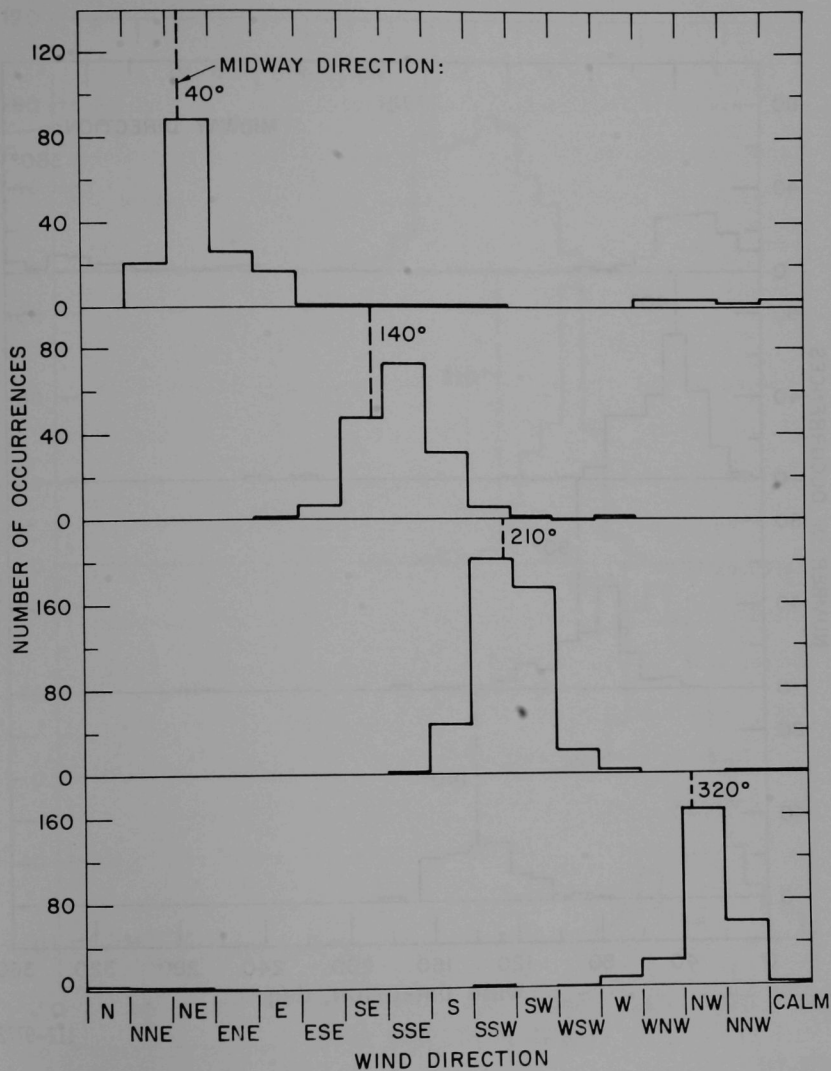
Figures 3.7, 3.8 and 3.9 show occasional wind direction differences of several tens of degrees, but at these stations with well-sited wind instruments the peaks of the distributions always fall within about 10 degrees of the concurrent Midway direction.

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There is reasonable agreement from  $40^{\circ}$  (NE),  $90^{\circ}$  (E), and  $140^{\circ}$  (SE), but agreement is poor from the other five directions.

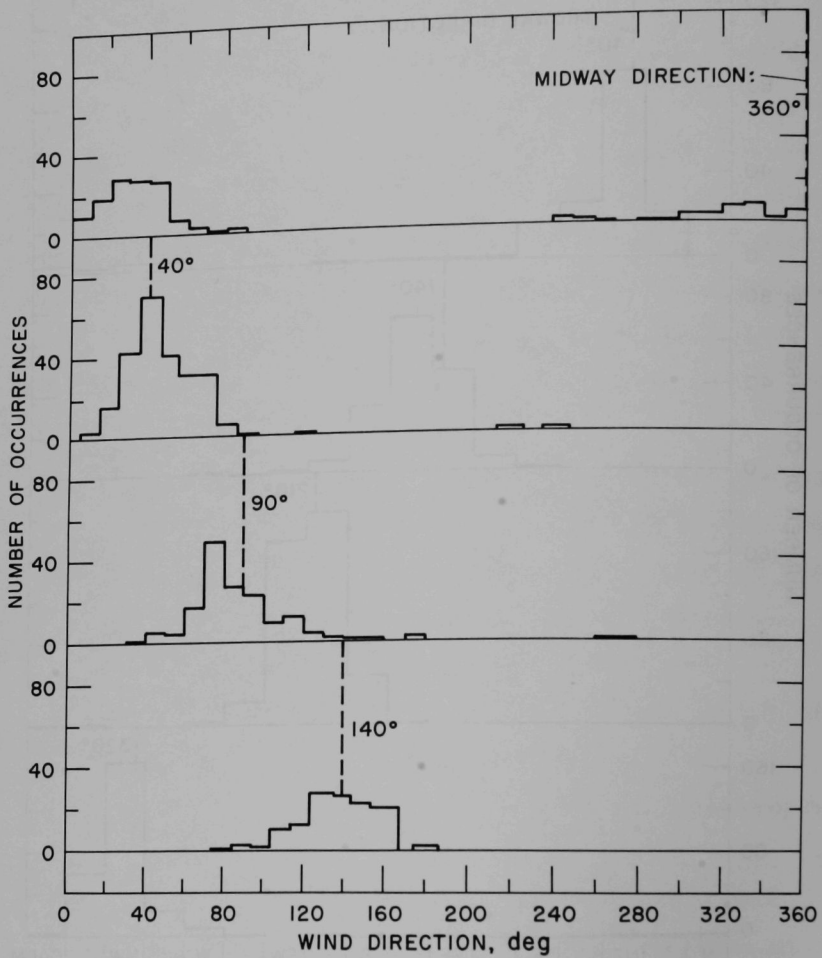
In contrast, TAM 7 (Fig. 3.11) shows good agreement with Midway from all eight directions studied.

Not all directions at TAM 6 are affected, so the problem there does not appear to be aerovane miscalibration, which would affect all directions in the same way. Furthermore, no evidence of seasonal or



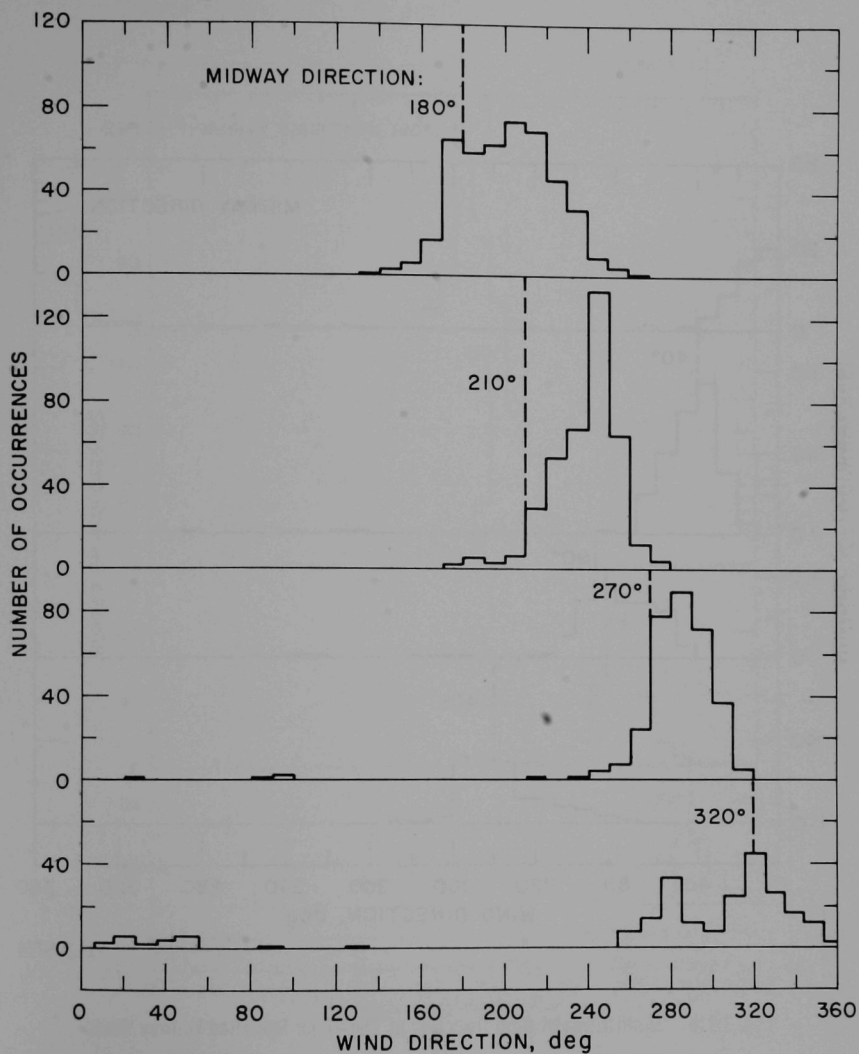
112-9771

Fig. 3.9 Distribution of Wind Direction at Argonne for Specified Midway Winds



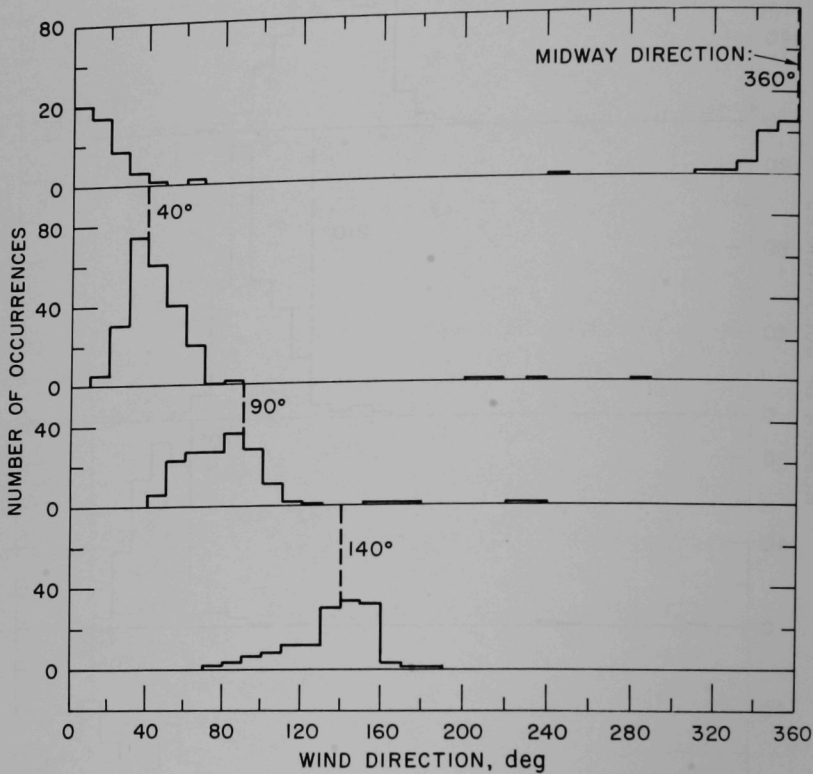
112-9772

Fig. 3.10a Distribution of Wind Direction at Tam-6 for Specified Midway Winds



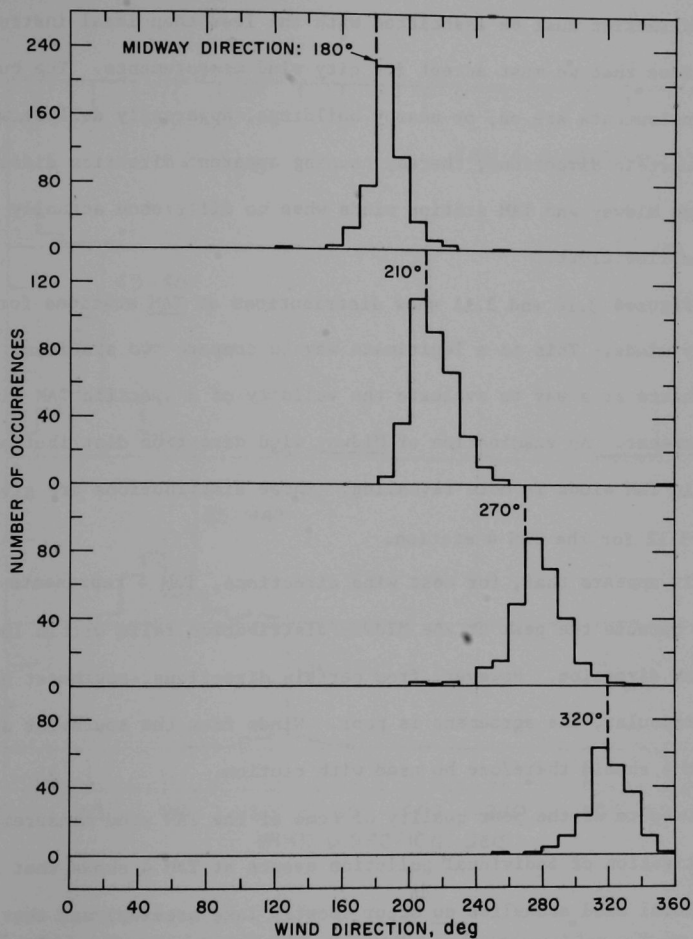
112-9773

Fig. 3.10b Distribution of Wind Direction at Tam-6 for Specified Midway Winds



112-9774

Fig. 3.11a Distribution of Wind Direction at Tam-7 for Specified Midway Winds



112-9775

Fig. 3.11b Distribution of Wind Direction at Tam-7 for Specified Midway Winds

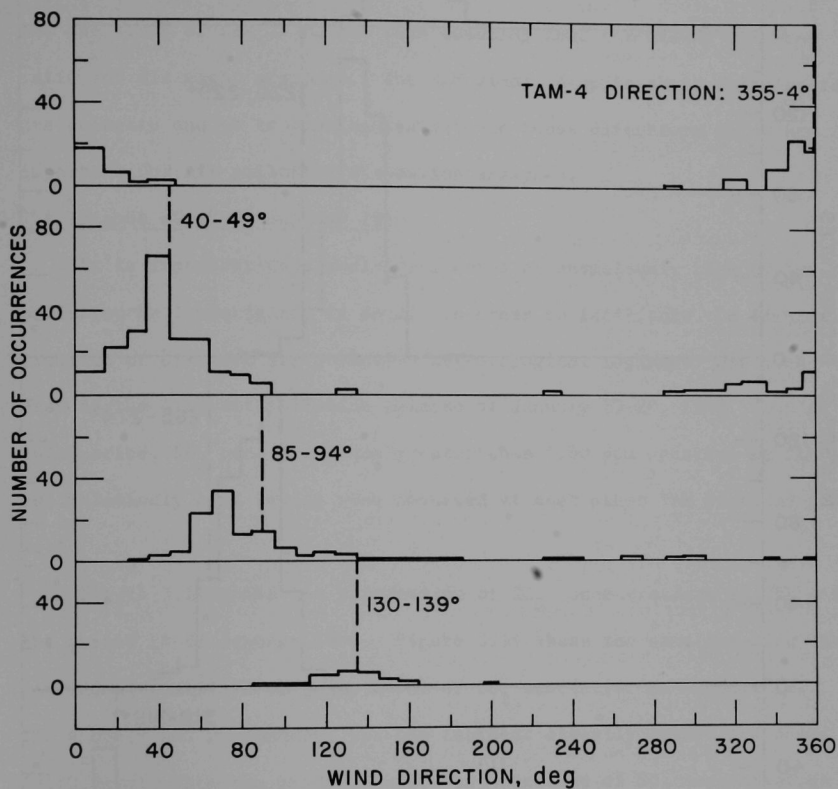
diurnal influences on the direction anomaly was found.

If miscalibration and seasonal and diurnal effects are not the cause of the problem, then it appears that the observed discrepancies in wind direction must be associated with the less than ideal instrument locations that we must accept for city wind measurements. The buildings the instruments are on, or nearby buildings, apparently deflect winds from certain directions, thereby causing apparent direction differences between Midway and TAM station winds when no difference actually exists in the flow aloft.

Figures 3.10 and 3.11 show distributions at TAM stations for certain Midway winds. This is a legitimate way to compare two stations, but it only hints at a way to evaluate the validity of a specific TAM wind measurement. An examination of Midway wind direction distributions for certain TAM winds is more revealing. These distributions are given in Fig. 3.12 for the TAM 4 station.

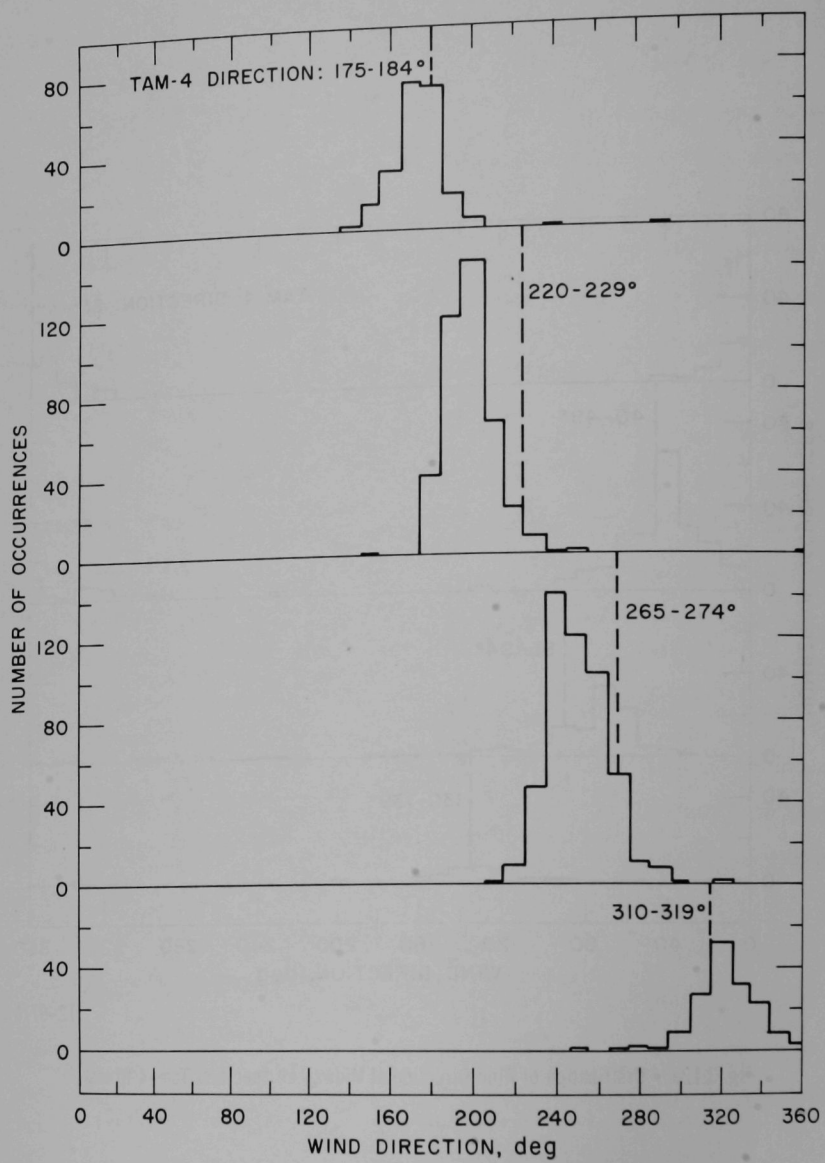
It appears that, for most wind directions, TAM 4 represents valid data, because the peak of the Midway distribution falls within  $10^\circ$  of the TAM direction. However, from certain directions, southwest and west in particular, the agreement is poor. Winds from the southwest and west at TAM 4 should therefore be used with caution.

Despite of the poor quality of some of the TAM wind measurements, investigation of individual pollution events at TAM 4 shows that important local wind anomalies do occur (mostly lake breezes) and that their magnitude is such that TAM measurements are accurate enough to detect them.



112-9776

Fig. 3.12a Distribution of Wind Direction at Midway for Specified Tam-4 Winds



112-9776

Fig. 3.12b Distribution of Wind Direction at Midway for Specified Tam-4 Winds

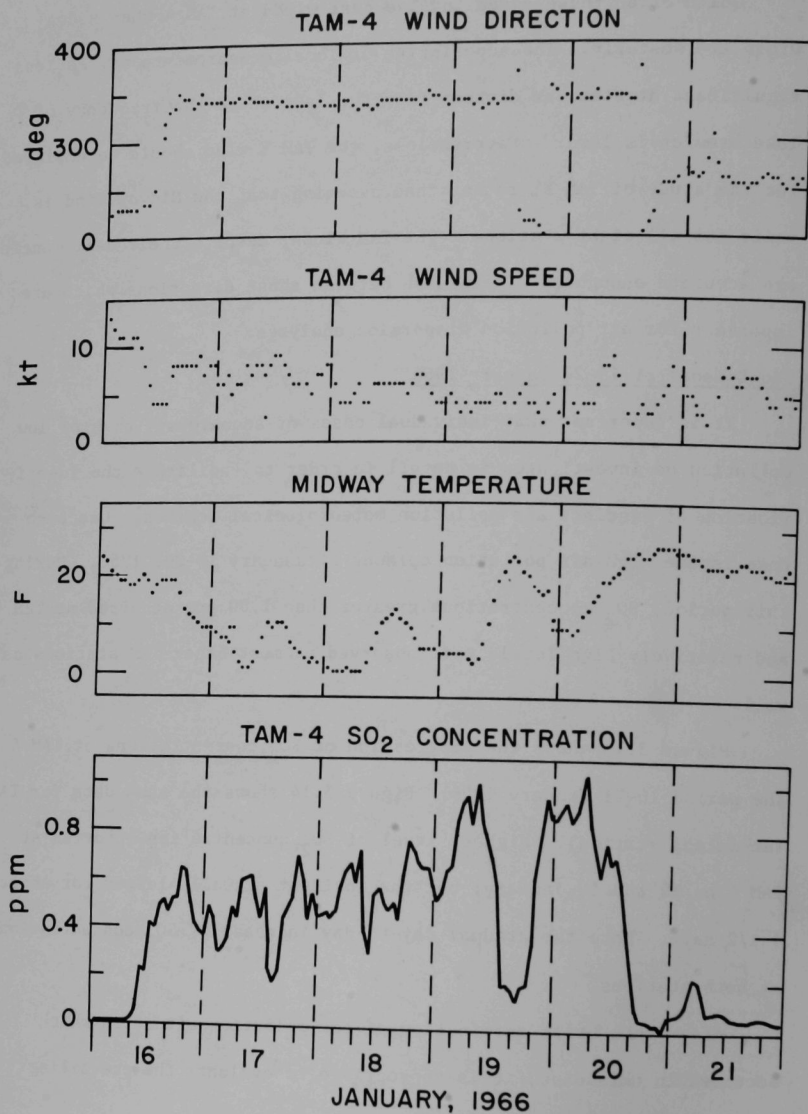
Quite often these cases involve east winds at TAM 4 when Midway winds are westerly. The superiority of local measurements may be less significant at stations distant from the lake where the frequency of lake breezes is lower. Nevertheless, the TAM X wind should be employed for the study of TAM X; rather than assuming that the Midway wind is valid for all eight stations. The TAM winds, despite their deficiencies, are accurate enough to distinguish between those directions which are important for air pollution dispersion analyses.

### 3.3.3 The Episode of 19-20 January 1966

It is important that individual cases of anomalously high or low pollution be investigated in detail in order to facilitate the identification of distinct air pollution meteorological regimes. One such case is the high air pollution episode of January 19-20, 1966. During this period,  $\text{SO}_2$  concentrations greater than 1.00 ppm occurred at TAM 4 and relatively high levels were observed at most other TAM stations as well.

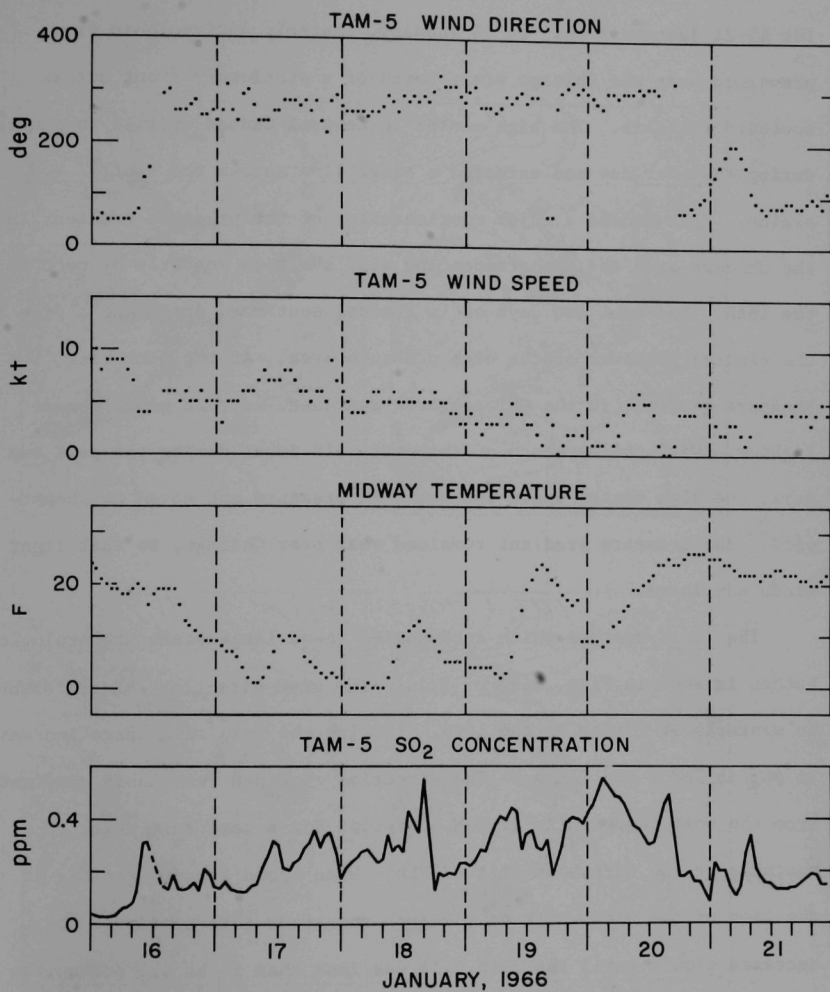
Figure 3.13 shows the progression of  $\text{SO}_2$  concentrations at TAM 4 for the period 16-21 January 1966. Figure 3.14 shows the same data for TAM 5 (an inland station). Highest level of  $\text{SO}_2$  concentration occurred at TAM 4 on 19 and 20 January, but the incident actually lasted for about 4-1/2 days. Note the gradual day-to-day increase of  $\text{SO}_2$  concentration at both stations.

After this brief examination of the pollution situation which occurred in this case, it is appropriate to evaluate the prevailing



112-9777

Fig. 3.13 Time Series of Tam-4 SO<sub>2</sub> and Winds, Plus Midway Temperature, 16-21 Jan. 1966



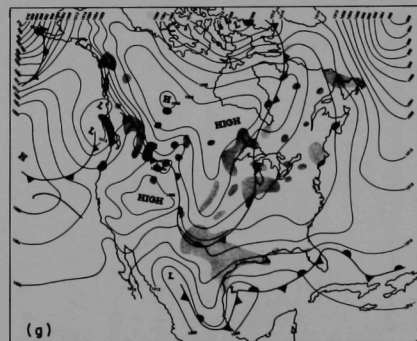
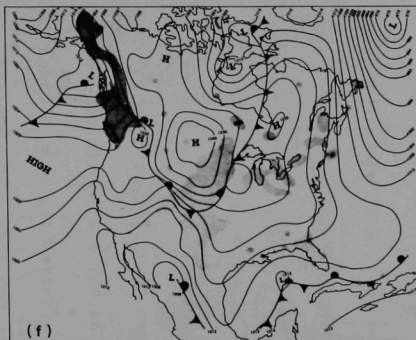
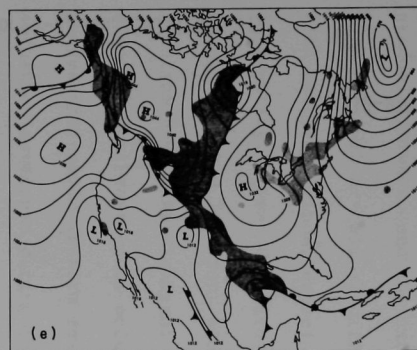
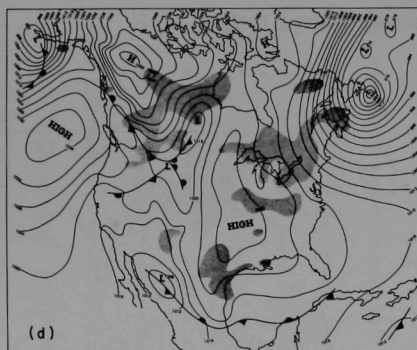
112-9778

Fig. 3.14 Time Series of Tam-5 SO<sub>2</sub> and Winds, Plus Midway Temperature, 16-21 Jan. 1966

synoptic weather pattern.

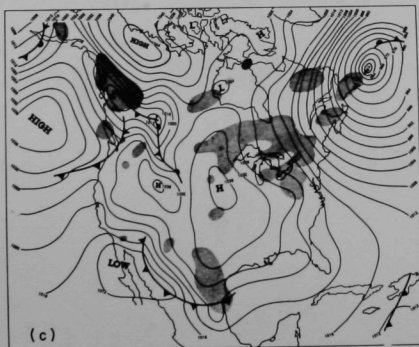
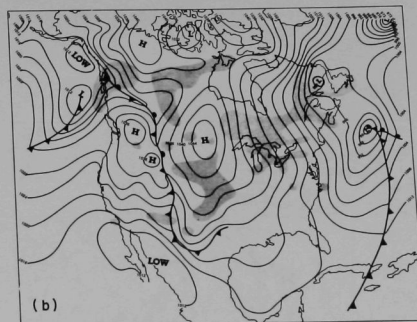
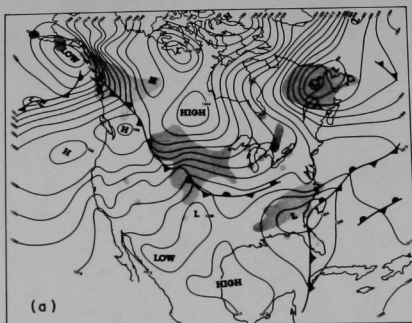
Figure 3.15 is a series of daily surface weather maps (at 1200 CST) for 15-21 January 1966. On 15 January, easterly anticyclonic flow prevailed over the Chicago area, north of a stationary front across southern Illinois. The high center in central Canada drifted southward during the next day and extended a ridge line across the central U.S. plains. This caused a major reorientation of the pressure gradient in the Chicago area and a corresponding wind shift to westerly by noon on the 16th. The next two days saw a gradual southward drift and a drop in the central pressure of the high pressure area. At the same time, the pressure gradient in the Chicago area weakened, so that winds became lighter. With the approach of the next cold front during the next two days, the high center again increased in pressure and moved northeastward. The pressure gradient remained weak over Chicago, so that light winds continued.

The local weather which accompanied these large-scale meteorological events is seen in Figs. 3.13 or 3.14. The wind direction shifted abruptly to westerly at midday on the 16th. (Notice the resulting large increases in  $\text{SO}_2$  at TAM 4 and TAM 5.) The direction remained remarkably constant from the west, especially at TAM 4, except for a temporary shift to easterly on the afternoon of the 19th. Wind speed dropped rapidly at the time of the wind shift on the 16th and after that continued to decrease slowly until the 20th. It was less than 10 kt all during the high pollution period. Temperatures dropped all day on the 16th as cold



112-9779

Fig. 3.15a Surface Weather Maps for 15-21 Jan. 1966 (1200 CST)



(a) 15 JANUARY

(b) 16 JANUARY

(c) 17 JANUARY

(d) 18 JANUARY

(e) 19 JANUARY

(f) 20 JANUARY

(g) 21 JANUARY

112-9780

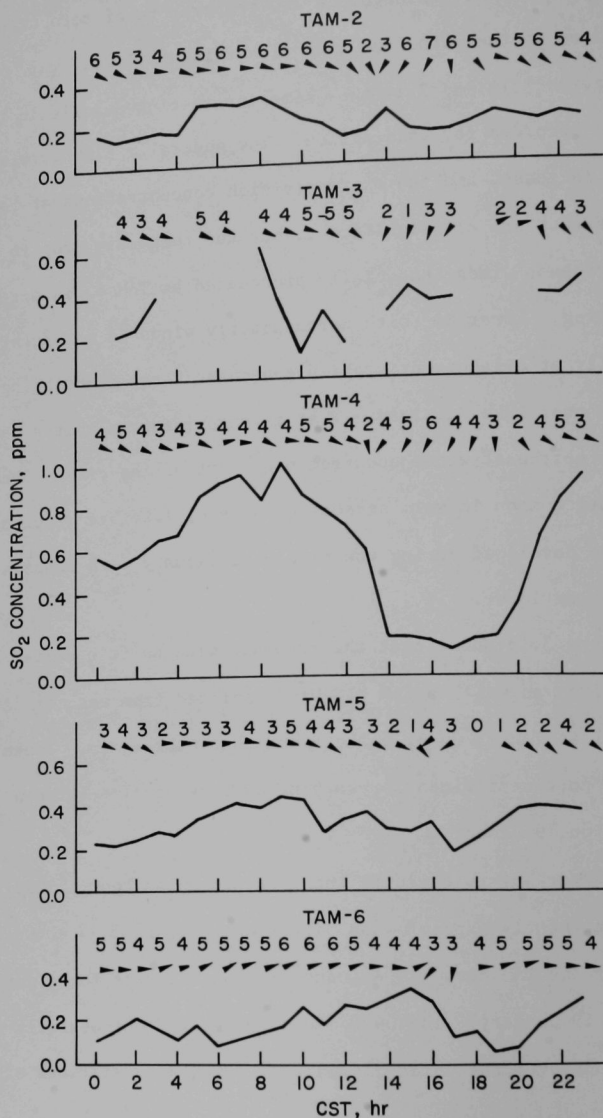
Fig. 3.15b Surface Weather Maps for 15-21 Jan. 1966 (1200 CST)

Canadian air reached Chicago. A low temperature of zero occurred just before dawn on the 18th, and gradual warming followed.

Figures 3.13 and 3.14 show some interesting details in the  $\text{SO}_2$  concentrations recorded for this period. The generally high levels, the gradual increase, and the extremely high concentrations at TAM 4 on the 19th and 20th are all significant, but the temporary drop in  $\text{SO}_2$  levels with northeast winds, especially pronounced at TAM 4, is particularly interesting. Lower  $\text{SO}_2$  with northeasterly winds is not surprising - especially at a lakefront station - because these winds bring in clean air from over Lake Michigan. What is surprising is that a temporary shift to northeast winds occurred over part of the city. Such occurrences are common in warm seasons because of lake breeze effects, this situation developed during the middle of January with temperatures in the 20's and lower.

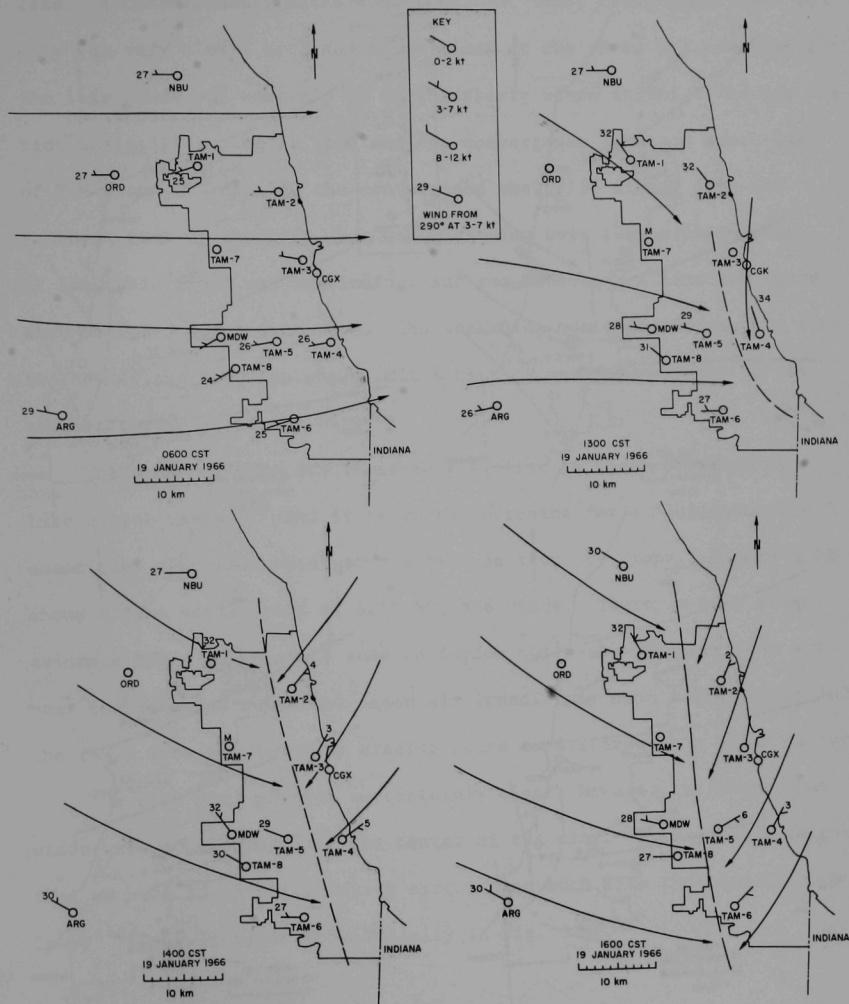
Figure 3.16 shows that the recorded wind shift occurred at other TAM stations as well as TAM 4. Winds shifted from west or northwest to northeast at TAM 2, 3, 4, 5 and 6 and then back again. These stations recorded northeast winds for varying periods of time between 1300 and 2000 CST on 19 January.

A better way to evaluate these events on an hour to hour basis is to examine hourly maps of wind direction. Figure 3.17 shows wind directions for the TAM network, Argonne and the airports for eight selected hours on 19 January. The 0600 map shows a straight westerly flow of light winds over the Chicago area. At 1300, most stations still had west



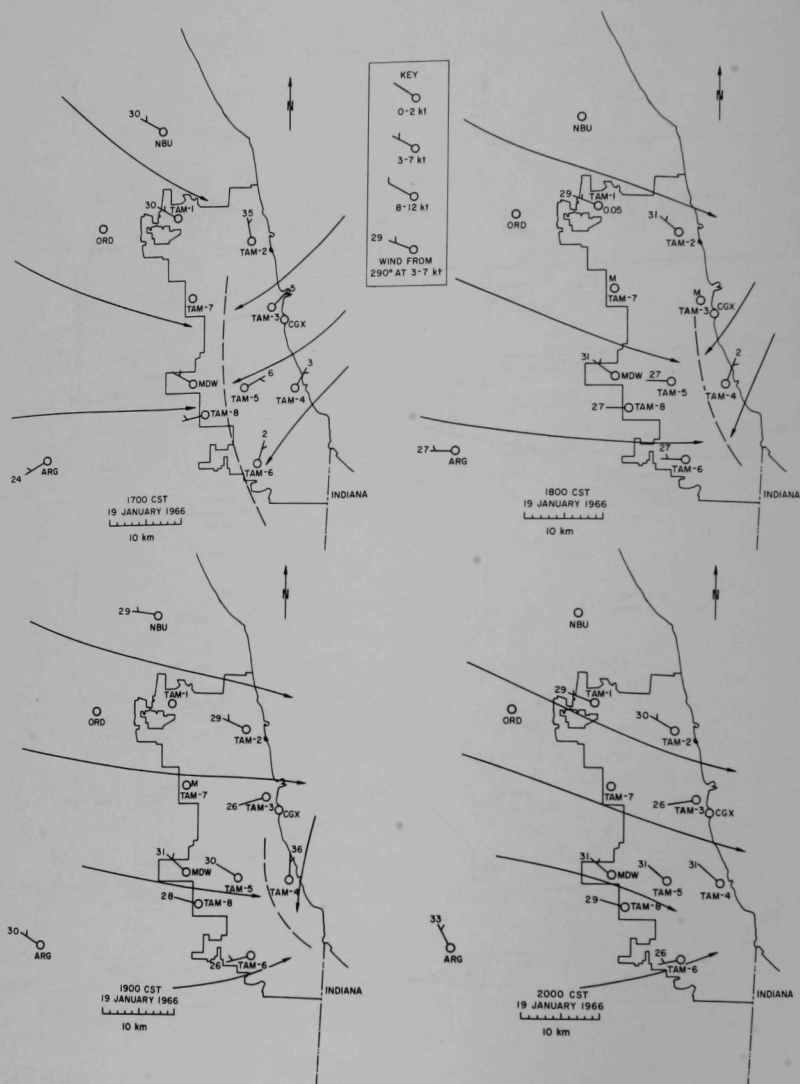
112-9781

Fig. 3.16 Time Series of SO<sub>2</sub> and Winds for Tam-2,-3,-4,-5 and -6 Jan. 19, 1966



112-9782

Fig. 3.17a Wind Field over Chicago on Jan. 19, 1966



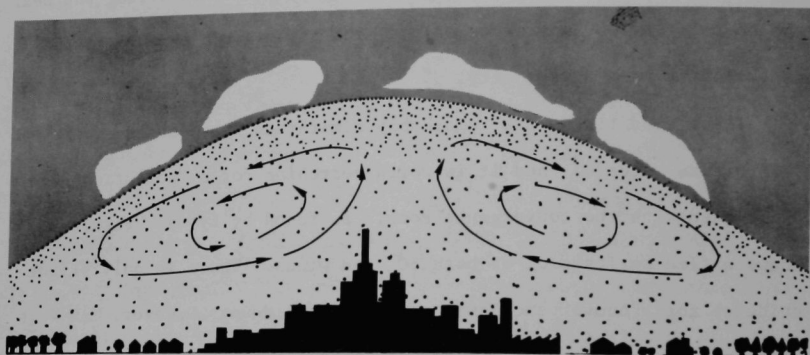
112-9783

Fig. 3.17b Wind Field over Chicago on Jan. 19, 1966

winds, but winds had begun to shift to more northerly directions near the lake. A convergence line is suggested. At 1400, convergence over the city was very clear, with northeast winds at the three TAM stations along the lake shore and westerly or northwesterly winds inland. The circulation was still strong at 1600 and the convergence line had moved west of TAM 5 and 6. At 1700 the convergence was still strong over the southern part of the city, but was weakening over the northern part. At 1800 this trend was continuing, and the convergence line had moved east of TAM 5 and 6 once more. The weakening continued during the next two hours; the 2000 map shows only a hint of weak convergence in the southeastern part of the city.

These wind fields are remarkably similar to those observed in lake breeze cases<sup>(15)</sup> and it is worth searching for a "pollution band" associated with the convergence zone, as found by Lyons. Figure 3.16 shows a time series plot of both  $\text{SO}_2$  and winds. There is only slight evidence for a convergence zone pollution build-up. However, TAM 4 is near the lake and would see clean air immediately upon a wind shift and the TAM 3 data has too many missing hours to distinguish a clear pattern.

The city wind pattern is certainly clear; however, it shows that winds were converging over the center of the city. This pattern suggests that we have found a city-rural circulation much like that described by Lowry<sup>(16)</sup> and pictured schematically in Fig. 3.18.



112-9784

Fig. 3.18 Schematic Diagram of a City-Rural Circulation (after Lowry, 1967)

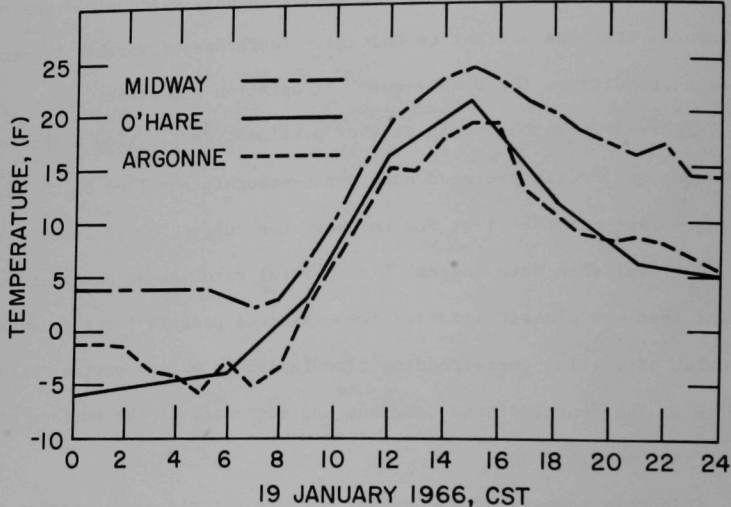
Two conditions are usually required for city-rural circulations to begin. The first is a temperature excess in the city; the second is sufficiently light ambient winds. Figure 3.19 shows a definite temperature excess at Midway Airport (in the city) relative to O'Hare Airport and Argonne (essentially rural sites). Figure 3.17 shows that surface winds were light in the Chicago area on the 19th, and Fig. 3.20 shows the same for winds aloft at Peoria, Illinois and Green Bay, Wisconsin - the two rawinsonde stations nearest to Chicago. Therefore, favorable temperature and wind conditions for a city-rural circulation did exist.

Figure 3.20 also reveals another pertinent fact: wind direction at Green Bay and Peoria averaged near north--roughly paralleled to the convergence line--in the first few km above the surface on 19 January.

The available data suggest a city-rural circulation somewhat different than the classical form. The classical case is for a somewhat circular city. The corresponding circulation is a ring vortex, with air rising in the center of the doughnut and returning to the surface at the outer perimeter.

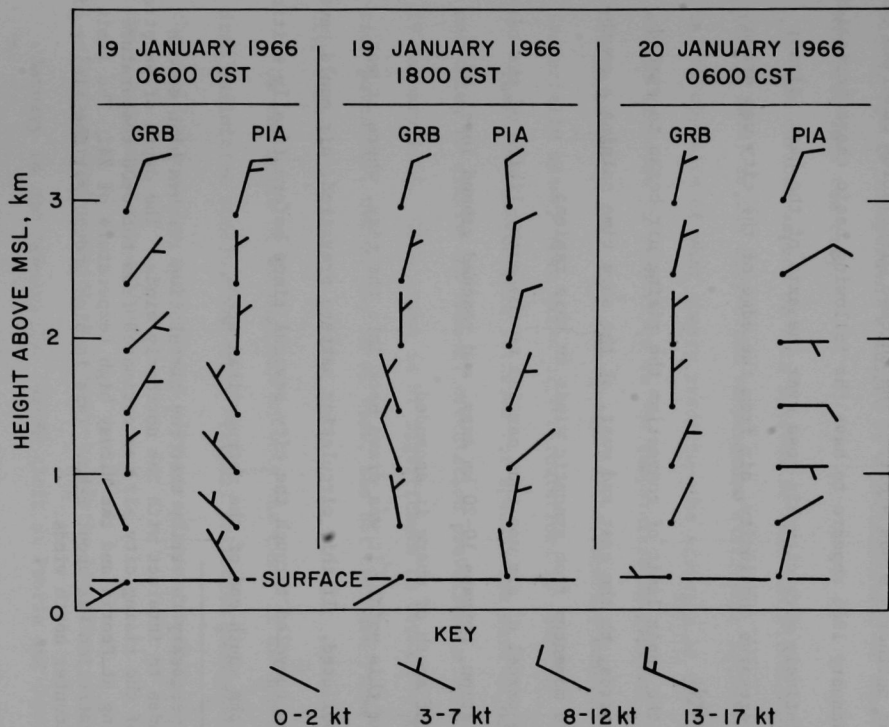
Chicago's topography and demography are not classical because the city lies along a lake shore. The heat island is not circular, but is instead a north-south band. Thus, Chicago's city circulation may have an axis of symmetry, rather than a center of symmetry.

For analysis of this episode, we must also consider possible interactions with the synoptic scale air flow. This point is not clear; perhaps the outside air simply flows around or over the city air "dome"



112-9785

Fig. 3.19 Temperature Variations at Midway, O'Hare and Argonne, Jan. 19, 1966



112-9786

Fig. 3.20 Winds aloft at Green Bay and Peoria Jan. 19-20, 1966

with little interaction between the two. There is some evidence that interaction did occur in this case, however. The wind fields at 1400 and 1600 (Fig. 3.17) show definite southerly components in both converging currents. This indicates that momentum is being transferred downward from the northerly winds aloft.\* The Chicago circulation observed on 19-20 January 1966 appears to have the following basic characteristics:

1. Relatively warm city air rose over the axis of the heat island;
2. To preserve continuity, air from the edge of the city was drawn inward;
3. At the upper limit of convection the rising air began to spread outwards, to the east and west, at the same time gaining a southward momentum from synoptic winds in this region;
4. The parcel of air was thus carried to the outer limits of the circulation, perhaps 10-20 km away, and reached ground level at a point south of where it ascended.
5. From this point, it was drawn back into the city, where it was repolluted. If this circulation pattern prevailed, air could have been recycled through the city several times before finally exiting at the south end of the metropolitan area.

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\* It is necessary to verify that the circulation reaches high enough altitudes to interact with the northerly winds. The depth of penetration of the rising city air was estimated from the 0600 temperature sounding at Peoria and the Midway high temperature of 24. The limit of penetration was about 1 km. This is high enough for the rising air to encounter north winds.

One additional item of evidence to support the existence of this kind of circulation is found in the recorded  $\text{SO}_2$  concentration of air arriving at TAM 4 from the northeast. Figure 3.16 shows concentrations near 0.20 ppm. This is an unusually high concentration for northeast winds, and is independent evidence of a recirculation of once-polluted air back into the city.

One curious aspect of this episode is that the circulation died (about 1900) as the city-rural temperature difference increased. This is the opposite of what theory predicts--the strength of the circulation should increase in proportion to the temperature difference. The explanation probably lies with some change in the external conditions (especially winds) that allow city circulations to continue.

There is considerable latitude for speculation here of course, but one thing is clear: an unusual circulation prevailed in Chicago on 19 January 1966. This event is of significance to Chicago's air pollution potential, and as far as we know, has not been described for this city before.

On the basis of an analysis of only one case, it is difficult to draw definitive conclusions about critical pollution parameters or their threshold values for permitting a city circulation in Chicago; however, two points are worth noting:

1. Surface winds outside the city were mostly less than 5 kt between January 18 and January 20. Winds aloft at Peoria and Green Bay were mostly less than 10 kt up to 700 mb on the day of the

circulation--January 19.

2. The city-rural temperature difference ranged from 3 to 10 degrees F on January 19. The larger values occurred at night.

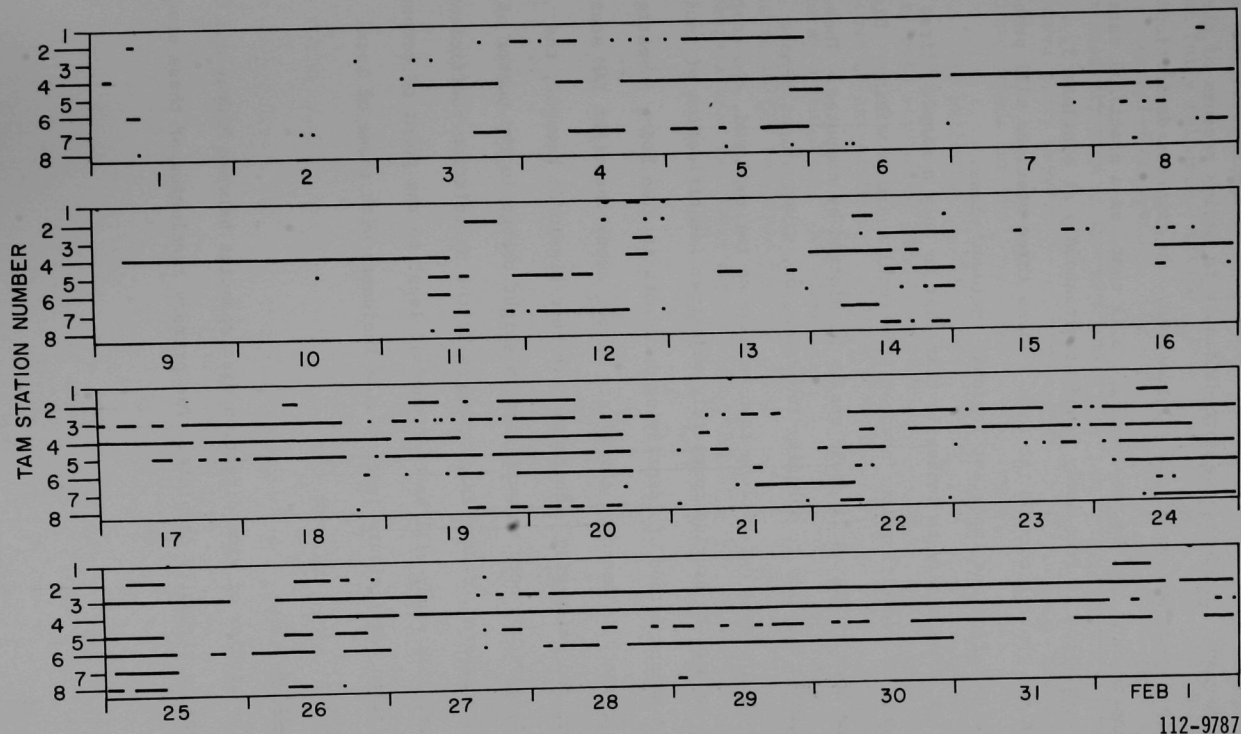
### 3.3.4 Identification of Air Pollution Incidents: Preliminary Results

The previous section describes a pollution incident which affected nearly the entire city. Incidents which affect only one or a few stations also require study. This section describes a study which was mounted in order to evaluate methods for the identification of such incidents.

An  $\text{SO}_2$  concentration of 0.20 ppm was arbitrarily chosen as a threshold value for an incident. The master file was then searched for all occurrences of  $\text{SO}_2 \geq 0.20$  ppm at the eight TAM stations during January 1966. Each occurrence found was plotted as a point in the time series shown in Fig. 3.21.

In general, it is reasonable to define a local incident as the occurrence of an hourly average  $\text{SO}_2$  concentration in excess of 0.20 ppm at only one station. (Probably some time duration should also be specified in order to define a threshold dose rate.) Similarly, it is reasonable that a regional incident should involve several stations and a city-wide incident all, or nearly all, of the eight Chicago stations.

Figure 3.21 shows that even in January 1966--a month of some extremely high  $\text{SO}_2$  concentrations--there were no hours where  $\text{SO}_2$  was  $\geq 0.20$  ppm at all eight stations. Nevertheless, some wide-spread pollution situations occurred--for example, on January 19th and 20th. Figure 3.21 suggests that



112-9787

Fig. 3.21 Time Series of Hourly Average SO<sub>2</sub> 70.20 ppm for Chicago Tam Stations, Jan. 1966

a city-wide incident should involve at least six of the eight stations.

Regional incidents are more difficult to define because of the many possible combinations of several stations. No rigorous definition is attempted here, but we see from Fig. 3.21 that, as a practical matter,  $\text{SO}_2 \geq 0.20$  ppm is frequently found simultaneously at stations 3, 4 and 5, in the central core of the city. These three stations will probably serve to define one important regional incident class.

It is necessary to emphasize that this is only a simple "first try" at incident identification; however, the results are promising. Displays in the form of Fig. 3.21 could easily be plotted by computer. These could be scanned visually to identify incidents, or, given slightly more rigorous incident definitions than we have so far employed, the computer could be used to provide completely objective identification of incidents.

A second method of identifying incidents is also being investigated. This approach is based on covariance of  $\text{SO}_2$  among the eight TAM stations. So far, two "city-wide" incidents have been examined; however, the results have not been encouraging: a slight change in the number of data hours considered, causes large changes in the correlation coefficients. However, this study will be continued at least to the point of comparing correlation coefficients in city-wide incidents with those of local incidents.

### 3.3.5 Conclusions

The studies of wind direction discrepancies between Midway and TAM stations is virtually complete. The primary conclusion of these studies

is that certain direction indications at some of the TAM stations are not fully reliable. Siting inadequacies probably cause the problem.

Detailed analysis of anomalous data points which appear to be excessively high or low with respect to temperature regression lines showed that, despite their deficiencies, TAM winds are preferred to Midway winds for the development of regression equations.

Air pollution regimes identification has proceeded on the basis of in-depth studies of anomalously high or low pollution levels. One case study of extremely high  $\text{SO}_2$  pollution has revealed a probable city-rural circulation. Additional case studies of this type will be undertaken in the immediate future. Computer-plotted time series of  $\text{SO}_2$ , temperature, and winds will be developed for these analyses.



## CHICAGO AIR POLLUTION DISPERSION MODEL

### 4.0 Emission Inventory

J. Roberts  
E. Croke

#### 4.0 Emission Inventory

##### 4.1 Field Emission Survey

The field survey effort to accumulate detailed, industrial SO<sub>2</sub> source emission data for the master data file was temporarily curtailed during this period. This decision was predicated on three considerations:

- 1) Sufficient point source emission data has been accumulated to test the effectiveness of the proposed statistical diffusion model for at least two of the TAM stations (Hyde Park and Lindbloom) and enough area source data is available to test the Model at all TAM stations.
- 2) The DAPC personnel who were engaged in the field emission survey were diverted, during this period, to the task of accumulating and processing the emission data associated with the July 2 air pollution abatement test (described in section 3.0). Since this exercise had a clearcut priority over the longer-range emission inventory effort, the latter was inevitably delayed.
- 3) The rate of accumulation of emission data prior to the abatement test exercise was sufficiently great to have created a backlog of processing work.

We anticipate that the inventory survey will be resumed during the forthcoming quarter to provide source information for the diffusion analysis studies and in order to support the optimal abatement strategy planning effort.

## 4.2 Stoker Monitors

The importance of residential and commercial fuel burning in determining  $\text{SO}_2$  levels throughout the city has been emphasized in section 2.1. While the relationship between these quantities appears linear over the whole range of  $\text{SO}_2$  concentrations, it appears that the variation in  $\text{SO}_2$  levels with temperature is slightly more complicated.

Firstly, there is the janitor function or diurnal fuel use pattern defined by Fig. 2.1. Secondly, there is strong evidence from profiles of  $\text{SO}_2$  vs. temperature that the slope of the fuel use curve changes abruptly near freezing. Thus, we are led to believe that the increase in fuel requirements per degree Fahrenheit for outside temperature below freezing is nearly twice the value for temperatures between  $30^\circ$  and  $55^\circ\text{F}$ .

In order to better understand the fuel requirements of coal fired boilers heating buildings in the 2-4 story category, and possibly to identify differences between residential and commercial fuel use patterns, we propose to continue the experimental program of monitoring automatic coal stokers.

Efforts in this direction last April acquainted us with several problems in the experimental set-up:

- 1) The instruments<sup>\*</sup> had to be tended each week to rewind the clock and renew the ink supply; 2) paper had to be shifted every two

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<sup>\*</sup> Esterline - Angus, clock-wound, pen recorders were used.

weeks; 3) pens clogged due to dirt in the basements; 4) various mechanical malfunctions occurred in the clock drive and paper take-up mechanisms; and 5) one building had a three speed stoker with a manual shift - requiring the janitor to note changes in gear ratios on our recording paper.

The first four and possibly all of these objections can be avoided by choosing a superior effective event recorder. The Simpson miniature event recorder, Model 2755, has these pertinent features:

- 1) No ink. Uses coated, pressure sensitive paper.
- 2) Automatic paper take-up via 110v a-c motor.
- 3) Long term recording: 32 days of continuous recording at .787 inches per hour.
- 4) Multiple channels: if stoker gear ratio can be sensed electrically, we should be able to monitor this, since up to 10 recording channels are available.
- 5) Accuracy: at .787 inches/hour (1 month/roll of paper) events of duration as short as 1.5 minutes can be resolved.

We propose to install two of these instruments as stoker monitors in residential buildings and possibly a third in a commercial establishment. The two apartment buildings studied briefly last April, are not suitable for the coming experiments: the six flat has been converted to gas heat; the court-type apartment house has the undesirable feature of a stoker gear box (1/3, 2/3, full speed) which is shifted by hand

and quite difficult to monitor. Therefore, the Chicago DAPC will have to negotiate with landlords for a new set of buildings. These would be monitored throughout the 1968-69 heating season.

#### 4.3 Coal Utilization in Chicago

Among the primary sources of information for the emission inventory and long range planning effort have been the Midwest Coal Producers Institute and the Association of Chicago Retail Coal Merchants. These organizations have supplied Argonne with a significant amount of data for the estimation of present and future coal use patterns in the Chicago Metropolitan area. This information is summarized in Tables 4.1 and 4.2, and Figures 4.1, 4.2 and 4.3, which represent estimates made by the coal producers and retailers of the origins, sulfur content and usage patterns for coal consumed in the Chicago area during 1966, and projections of the retail and industrial coal markets to 1980. On the basis of the fuel use data supplied by the coal community, a supplementary emission source maps similar to that shown in Fig. 4.4 have been developed for each TAM station.

TABLE 4.1  
TONNAGE DELIVERED IN 1966 \*

TONS OF SO<sub>2</sub> - % SULFUR

CHICAGO AREA AND WITHIN ONE MILE OF CORPORATE LIMIT

SULFUR RANGE

	<u>0-1.5</u>	<u>1.5-2.0</u>	<u>2.0-2.5</u>	<u>2.5-3.5</u>	<u>3.5-4.0</u>	<u>TOTAL</u>
<u>TONS OF COAL</u>						
<u>RETAIL</u>						
Midwestern	245,945	28,757	98,934	998,737	977	1,373,350
Eastern	1,012,651					1,012,651
Misc.	8,222					8,222
Sub-Total	<u>1,266,818</u>	<u>28,757</u>	<u>98,934</u>	<u>998,737</u>	<u>977</u>	<u>2,394,223</u>
<u>INDUSTRIAL</u>	306,941	82,538	110,279	1,540,855	9,118	2,049,731
<u>UTILITY</u>				4,236,873	2,366,957	6,603,830
<u>TOTAL</u>	<u>1,573,759</u>	<u>111,295</u>	<u>209,213</u>	<u>6,776,465</u>	<u>2,377,052</u>	<u>11,047,784</u>

TONS OF SO<sub>2</sub>

<u>RETAIL</u>						
Midwestern	6,354	864	4,715	57,118	69	69,120
Eastern	22,451					22,451
Misc.	166					166
Sub-Total	<u>28,971</u>	<u>864</u>	<u>4,715</u>	<u>57,118</u>	<u>69</u>	<u>91,737</u>
<u>INDUSTRIAL</u>	7,603	2,546	5,284	92,302	659	108,394
<u>UTILITY</u>				286,628	170,952	457,580
<u>TOTAL</u>	<u>36,574</u>	<u>3,410</u>	<u>9,999</u>	<u>436,048</u>	<u>171,952</u>	<u>657,711</u>

AVERAGE % SULFUR

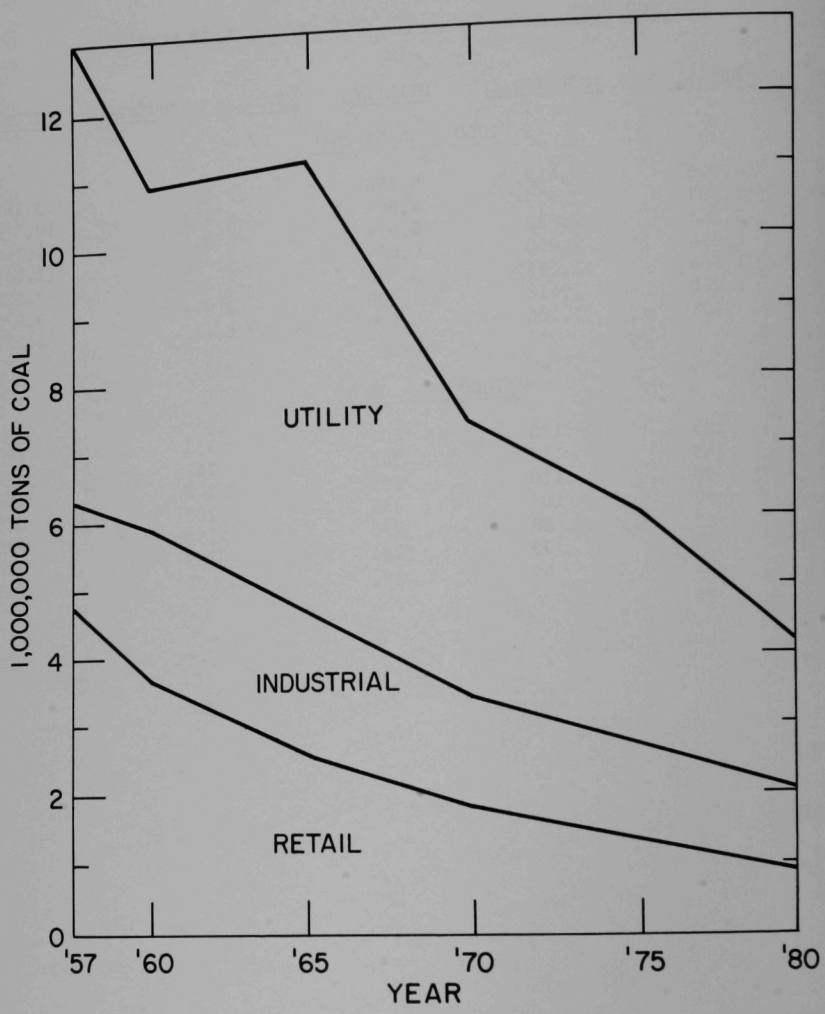
<u>RETAIL</u>						
Midwestern	1.29	1.50	2.38	2.86	3.53	2.52
Eastern	1.11					1.11
Misc.	1.01					1.01
Sub-Total	<u>1.14</u>	<u>1.50</u>	<u>2.38</u>	<u>2.86</u>	<u>3.53</u>	<u>1.92</u>
<u>INDUSTRIAL</u>	1.24	1.54	2.40	3.00	3.61	2.64
<u>UTILITY</u>				3.38	3.61	2.46
<u>TOTAL</u>	<u>1.16</u>	<u>1.53</u>	<u>2.39</u>	<u>3.22</u>	<u>3.61</u>	<u>2.98</u>

\* RETAIL TONNAGE APRIL 1966 THRU MARCH 1967

TABLE 4.2  
TONNAGE AND SO<sub>2</sub> PROJECTIONS

CHICAGO PLUS AREA WITHIN ONE MILE OF CORPORATE LIMIT

<u>YEAR</u>	<u>RETAIL</u>	<u>INDUSTRIAL</u>	<u>UTILITY</u>	<u>RETAIL &amp; INDUSTRIAL</u>	<u>TOTAL</u>
<u>1000 TONS OF COAL</u>					
1957	4,846	2,412	5,886	7,258	13,144
1960	3,693	2,229	4,948	5,922	10,870
1965	2,564	2,082	6,534	4,646	11,180
1966	2,394	2,050	6,604	4,444	11,048
1970	1,764	1,666	3,900	3,430	7,330
1975	1,260	1,418	3,300	2,678	5,978
1980	921	1,206	2,100	2,127	4,227
<u>1000 TONS OF SO<sub>2</sub></u>					
1957	205	128	407	333	740
1960	149	118	342	267	609
1965	98	110	459	208	667
1966	92	108	458	200	658
1970	62	88	275	150	425
1975	38	75	234	113	347
1980	24	64	147	88	235



112-9788

Fig. 4.1 Chicago Coal Consumption 1,000,000 tons Burned

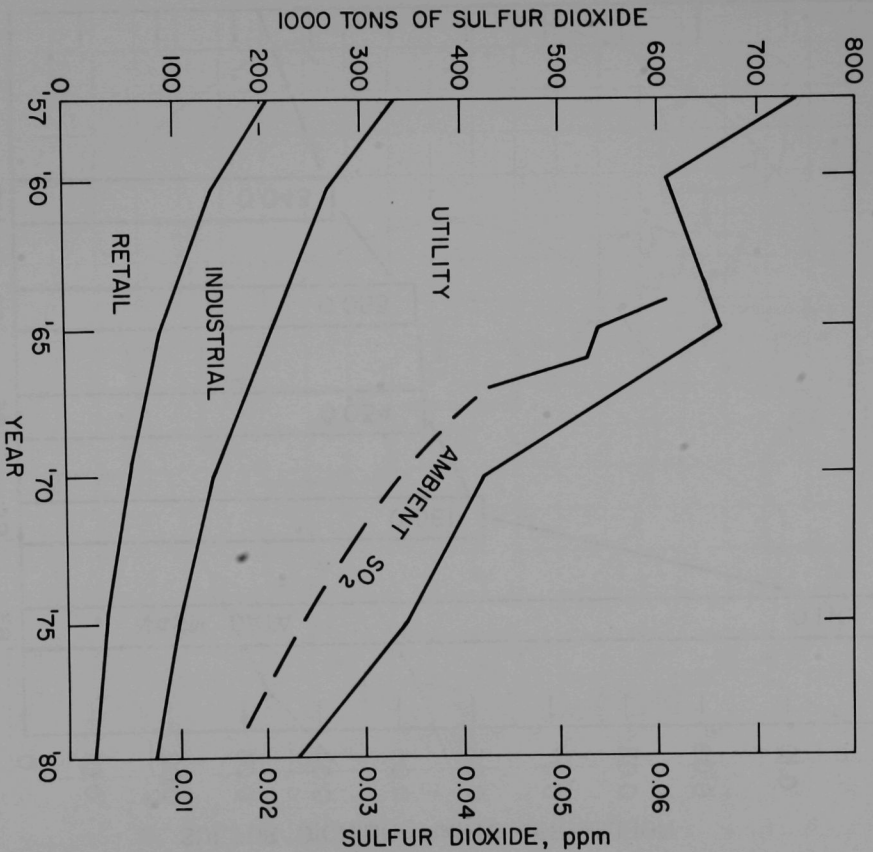


Fig. 4.2 Chicago Yearly  $\text{SO}_2$  Emissions Projected to 1980

112-9789

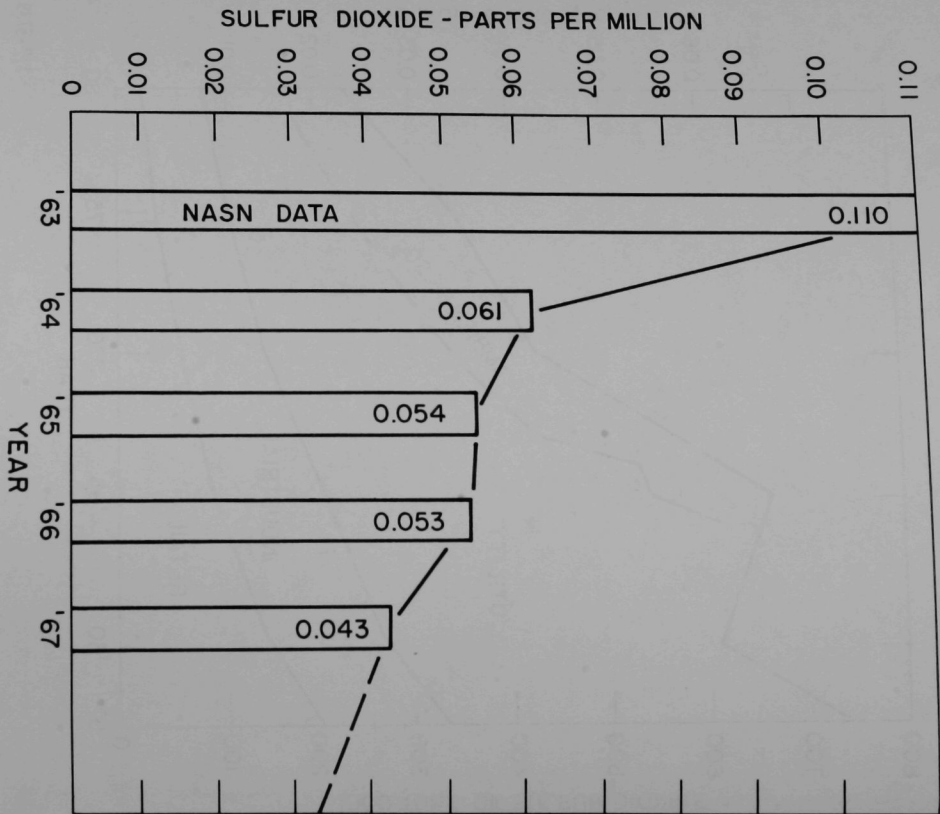
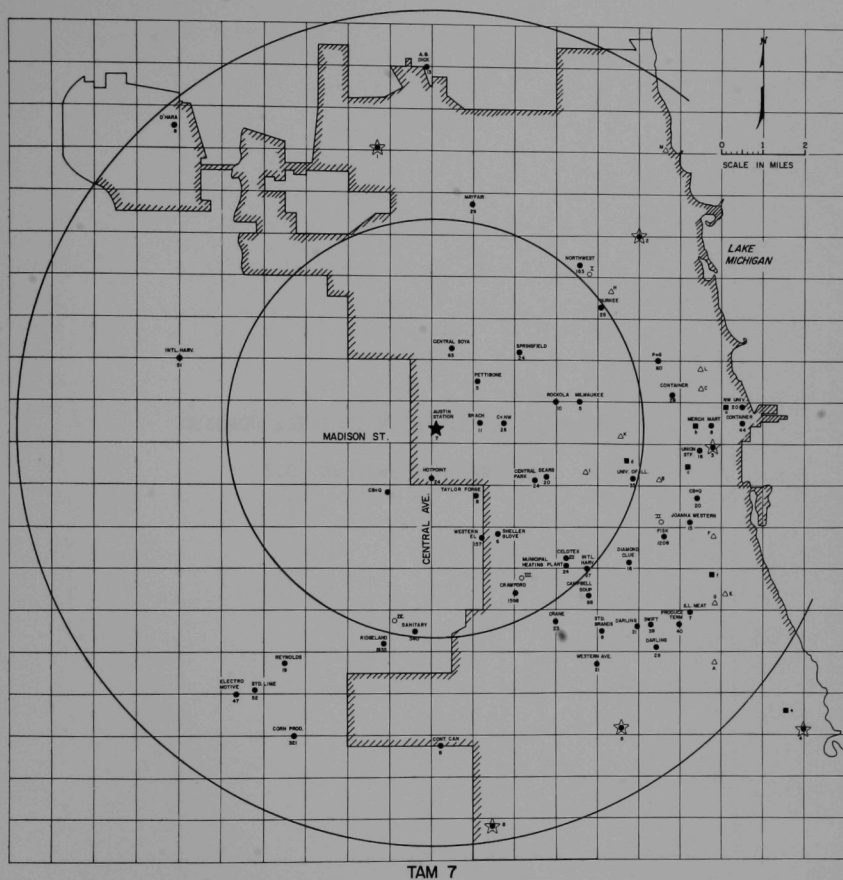


Fig. 4.3 Chicago Average Yearly SO<sub>2</sub> Emissions - to 1967

112-9790



112-9791

Fig. 4.4 Tam-3 Oriented Source Map



## CHICAGO AIR POLLUTION DISPERSION MODEL

### 5.0 Applied Programming

A. Kennedy  
J. Gregory  
J. Anderson

5.0 Applied Programming

During this period, the applied computer programming effort in support of the system analysis studies and the operations manual (see Section 7.0) project consisted of a series of service functions. These included:

- 1) Development of plotting routines for visual display of meteorological and air quality data.
- 2) Development of emission data processing algorithms and creation of emission data tapes for input to the master information system.
- 3) Acquisition and modification of a stepwise discriminant analysis computer code, adaptation of this code to the Argonne, IBM 360-75 computer and incorporation of the code into the master information system.
- 4) Development of algorithms for met set processing and array formation within the master information system.
- 5) Development of a computer routine for calculating approximate urban mixing layer depths.
- 6) Adaptation of the source-oriented "integrated puff"  $\text{SO}_2$  diffusion model for use with a standard linear programming package code in the Commonwealth Edison optimal incident strategy pilot study (see Section 6.0).
- 7) Adaptation of the optimal incident strategy system for use with computer teleprocessing equipment.

Since the results of the computer programming efforts described above are discussed in some detail in other sections of this report, further elaboration is not considered to be necessary here. The details of all significant applied programming tasks undertaken during the course of the air pollution program either have been or will be documented separately from the quarterly reports, since these do not bear directly on the course of the technical and economic studies of air pollution.

1. The first of the three main points of the report is that the

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## CHICAGO AIR POLLUTION DISPERSION MODEL

### 6.0 Air Pollution Economics and Abatement Strategy

K. Croke  
A. Kennedy  
D. Parsons

## 6.0 Abatement Strategy and Economics

### 6.1 Relationship of Prediction and Control Models

The selection of a particular control model for pollution abatement is closely linked with the accuracy and level of aggregation of sources used in the predictive model. The coupling of a control model which recommends highly specific and sensitive control with a low accuracy predictive model only gives an illusion of strict air quality controls. The choice of the control model must be such that not only will the predictive model be capable of accurately indicating when control should be exercised, but also be able to predict the consequences of each alternative control strategy.

The time horizon of the predictive model must also affect the choice of control. In a meteorologically based prediction model, the longest time horizon one may reasonably expect is twenty-four to forty-eight hour forecast. Since the level of confidence in the accuracy of the prediction decreases as the time horizon lengthens, it may be expected that accurate predictions would allow considerably less time to implement a control scheme. The possibility of rapid deviation from a weather prediction further necessitates a control program with a capability for rapid adaptation to the revised prediction.

The level of aggregation of sources in the prediction model will influence the nature of the control model with respect to the level of aggregation of the sources under control, the type and timing of the control of their emissions, and the ability of the model to change with

revised predictions. Using a physical dispersion model, a disaggregated point source predictive and control scheme is possible, but the accuracy of purely deterministic physical dispersion models has not been satisfactory to date. A high degree of disaggregation in statistical regression models generates the usual difficulties of distinguishing specific source effects from random disturbances in the system. This is particularly true when the system involves meteorological variables. Higher aggregation in the prediction model demands higher geographical aggregation in the source emission control.

## 2 Types of Control

As shown above, the nature of the control model will depend on the type of prediction model used. Several varieties of emission control are possible depending on the objective of the program. The control program which needs the least amount of predictive inputs is a coal sulphur content restriction program which reduces the total amount of  $\text{SO}_2$  emitted into the atmosphere regardless of its dispersion. This program seeks to lower  $\text{SO}_2$  concentrations on the basis of some type of hypothetical average monthly or yearly city-wide concentration. Without a meteorological prediction scheme, this is the only type of control possible.

The second general type of control takes into account temporal variations in concentrations based on meteorological conditions. It seeks to reduce the  $\text{SO}_2$  emission only during those periods defined to be a pollution incident. For this type of control, a prediction model

is necessary; however, the model need only predict the occurrence of an incident and not any geographical air profile of the city during the incident. This type of control seems most appropriate for two or three day city-wide inversions in which the air quality of the whole city is threatened.

A third type of control model requires a prediction model which forecasts a pollution profile for a number of different areas of the city. Differential restrictions could then be placed on  $\text{SO}_2$  emissions in each region depending on meteorological conditions and the emission pattern of the area. Further disaggregation in the model could be affected by treating high or low sources separately depending on the conditions of the incident. Each further disaggregation of the decision variable of the control model makes increased demands on the predictive scheme. The final disaggregation is, of course, a source specific model in which each source can be controlled separately. It should be clear that the greater disaggregation possible, the more economically the control scheme can bring about the desired air quality.

Restriction of  $\text{SO}_2$  emission for any of the incident type control programs may be brought about in two ways. The first method is a level of operation restriction for the period of the incident. This strategy can be used at any level of aggregation previously mentioned and can be imposed on any unit in the city. The second method is a fuel switching scheme designed to switch plants over to natural gas or low sulphur coal for the duration of the incident. Only dual fuel boilers are capable

of this conversion, of course. There are also restrictions on the total amount of gas that could be made available during the heating season for pollution purposes. As yet the economics of abatement is not well enough researched to determine whether fuel switching or level of operation control is more economical. Combinations of both strategies may well be necessary.

### 3 Incident Control

It has been the purpose of this study to develop an incident control model and to apply this model in a pilot study to some subsection of the urban economy. Some of the advantages and disadvantages associated with attempting such incident control strategies are discussed in this section.

#### 3.1 Advantages of Incident Control

1) Control plans aimed at controlling specific incidents possess certain advantages from a medical, meteorological and economic standpoint over coal sulphur content control. From a medical standpoint, it is fairly well established that the harmful effects of  $SO_2$  concentrations are linked to dosage rates so that public health objectives dictate a control reflecting these temporal variations in air quality, rather than just an average decrease in  $SO_2$ . 2) From an economic point of view, it is more efficient to plan for high concentration periods by using incident control. Meteorological conditions may indicate only the existence of local or short duration incidents, in which case, short term operational control would be far less disruptive to the

urban economy as a whole. The scarcity of "clean" fuels during certain seasons would also dictate the necessity of short term management and allocation of these fuels during high incident periods for the most efficient and economical abatement program. 3) An adaptive program of fuel and level of operation control would also be more specific to the type of incident with respect to the contributing sources. High concentrations in a given area may be caused by different emission sources depending on the particular wind conditions, source characteristics, etc. Operational control can reflect these distinctions so that the fewest number of units in the city will be affected. This is in keeping with the overall objective of the program of maintaining air quality with the least economic disruption.

#### 6.3.2 Difficulties of Incident Control

The difficulties of operational control lie not only in the increased demands on the prediction models, alluded to in 6.2, but also in the economic constraints placed on the use of incident control. There are certain activities, such as the generation of electric power, which cannot be interrupted under any circumstances. Operational control schemes must take account of these activities in attempting the allocation of fuels and level of operation control. Certain other activities can be interrupted only at great cost. Blast furnaces in the steel industry would fall in this category. The timing and duration of the interruption as well as the cost structure of the industry involved greatly affects the economics of abatement. Aggregation of industries

according to operation scheduling and cost structure will be necessary, but the greater the degree of aggregation, the higher the cost of the abatement program will be.

As noted above, the scarcity of clean fuels during certain seasons generates another problem for any abatement plan. Under any given set of conditions, the most efficient use of clean fuels may demand concentration of their use in only certain industries. An abatement program must also account for the rationing of clean fuel throughout the whole of the high incident season. Excessive employment of clean fuels early in a high incident season may prohibit their use for incidents later in the year. All these difficulties place a computational and analytical burden on the incident program to effectively reflect the total urban system.

#### Commonwealth Edison Company Pilot Study

A pilot study of the Commonwealth Edison Company (CECO) has been completed which explores alternative solutions to the difficulties of operational control enumerated above and constitutes the first operational test of a control model. The objective of this study was to test an incident control model which would yield control programs that are physically and economically compatible with CECO operations and simultaneously keep the pollution levels at an acceptable level. The predictive inputs employed by the control model were based on a source-oriented physical dispersion model (Davkern-described in ANL-ES-CC-002), but the control model was so constructed that it could incorporate the statistical predictor under development at ANL.

The Commonwealth Edison Company was a logical choice for this study for the following reasons:

1. CECO operations are subject to most of the types of economic constraints that a control program would encounter on a city wide basis;
2. A large inventory of accurate emission and air quality data available to provide an excellent validity check for the model;
3. A power generating network is amenable to both of the types of control described above;
4. Power generating stations tend to be among the largest single sources of  $\text{SO}_2$  in the city environment.

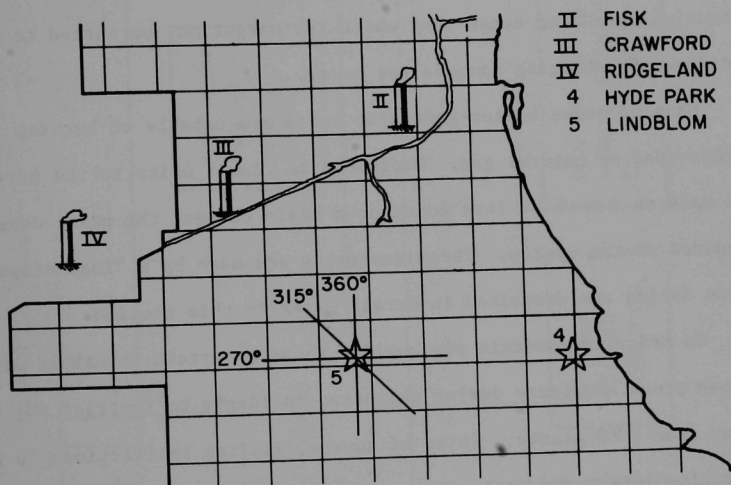
#### 6.4.1 The Pilot Study Control Subsystem

A subsystem of the total CECO network was selected as the object of this study. This subsystem is shown in Figure 6.1. It includes the Fisk, Crawford and Ridgeland plants and the Lindbloom and Hyde Park TAM stations. This configuration was chosen because:

1. The Fisk, Crawford and Ridgeland plants are three of the largest plants in the urban power system, and
2. The physical layout of this subset of plants is such that, for certain meteorological conditions, their  $\text{SO}_2$  emissions might be expected to affect the air quality detected at the TAM stations.

#### 6.4.2 Physical Characteristics of the Power Generation System

The Commonwealth Edison Company is part of a major network of power companies distributed throughout the North Central United States. These companies are linked together in order to permit electrical power



112-9792

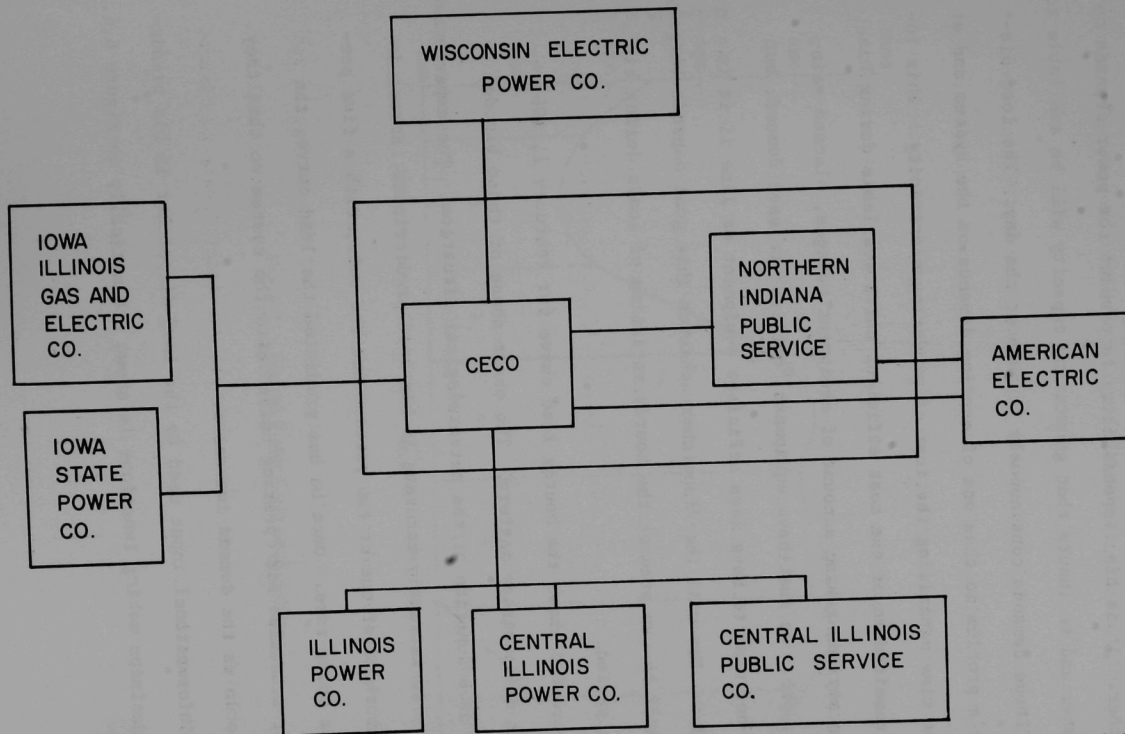
Fig. 6.1 Power Plant Pilot Study System

to be transferred from one utility system to another in case of emergencies or under circumstances when it is economically advantageous to do so. CECO's position in this network is shown schematically in Figure 6.2.

CECO generates its own power in a 15 plant network distributed over Northern Illinois. Each plant contains a number of generator units of varying size and efficiency. Each of these units has an effective operating range over which its output may be varied to meet continuously changing demands for power.

Many of these boiler-generator units are capable of burning either coal or natural gas. Decisions to commit units to the network are made on a more or less continuous basis to meet the power demands required of the system. These decisions are made by a "load dispatcher," whose duties are described in detail later in this section.

In order to maintain air quality above a certain threshold limit, it may prove necessary during pollution incidents to restrict  $\text{SO}_2$  emissions from CECO plants. This, of course, implies restrictions on unit operating levels and fuel usage, which, in turn complicates the load dispatcher's decision making process. It is, therefore, important to understand the process by which units are committed to the system and power demand is distributed among committed units so that controls can be imposed which are economically feasible and least likely to disrupt normal CECO operations.



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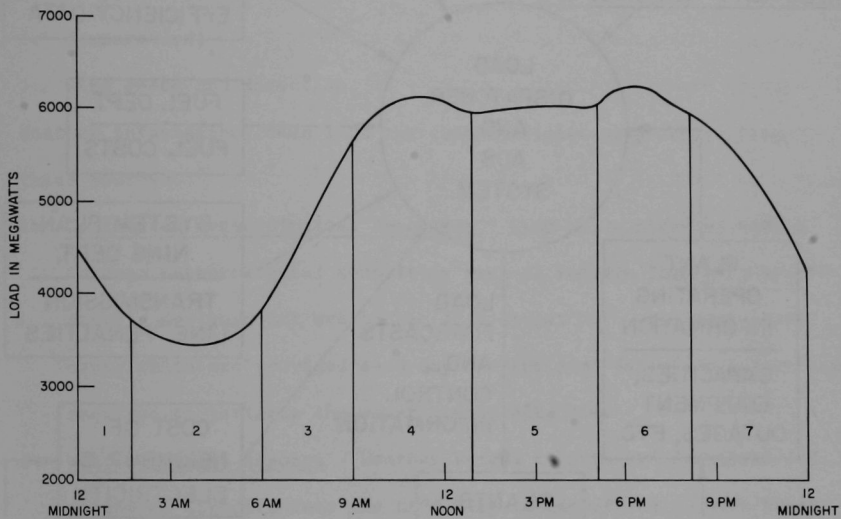
Fig. 6.2 Power Company Network

### The Power Dispatching Decision Process

The focal point of the CECO power generation system is the load dispatcher. It is his responsibility to predict the power demands on the system and to insure that generating capacity will be available to supply these demands continuously throughout the day. The load dispatcher's problem is thus one of meeting demands on the system and at the same time minimizing the cost of producing electricity. This involves commitment of the most efficient units available during his planning period, taking account of equipment outages, planned maintenance, etc. He must have equipment "on line" to meet demand, but he does not wish to have less efficient equipment on line if it is not needed. How well the dispatcher achieves this goal depends largely on how well he can predict the hourly variation of loads during his planning period.

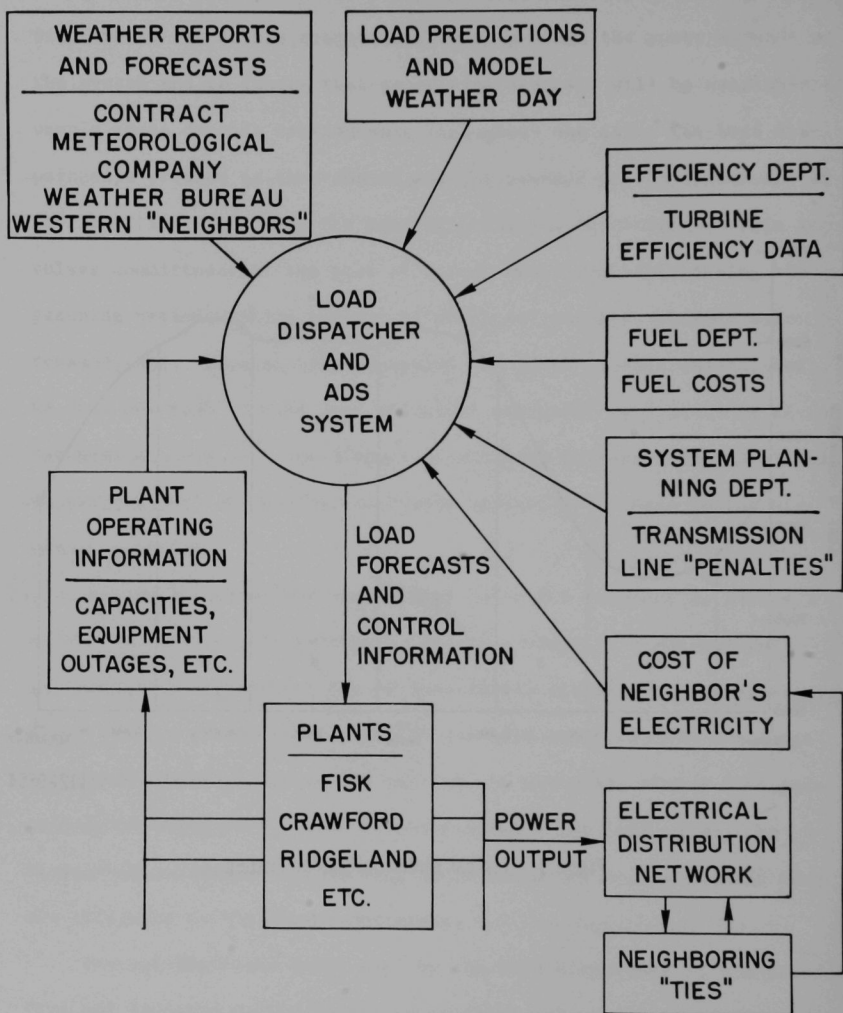
Figure 6.3 shows the hourly load curve for February 1, 1966 - a typical daily winter pattern. The exact shape of these bimodal patterns is a function of the meteorological situation. The experienced dispatcher is extremely accurate in his load predictions. Errors in the neighborhood of one or two percent are the rule, with a five percent error being rare. Once he has predicted the load curve, the dispatcher schedules his "peaking units" onto the system so that they are available as the demand increases.

The informational input used by the load dispatcher in his prediction and decision making functions is shown schematically in Figure 6.4.



112-9794

Fig. 6.3 Typical Winter Daily Load Pattern



112-9795

Fig. 6.4 Utility Power Generation Control System

## Weather Information

Since weather conditions cause much of the variability in system load demands, one of the most important inputs to the dispatcher is the short range weather forecast. Those meteorological parameters which are considered to effect the system most are:

1. Sky condition (i.e., percent cloud cover, cloud type, light intensity, etc.);
2. Temperature;
3. Wind speed and direction.

Weather information comes into the central dispatching office from three sources.

1. Contracted Meteorological Forecasts CECO has contracted with a Chicago meteorological consulting firm to receive forecasts specifically designed for use by the load dispatcher. The four forecasts which are provided each day are the most important parameters required to estimate the power demand schedule.
2. Weather Bureau Reports Weather bureau reports and forecasts are teletyped directly into the CECO dispatching office. These report are continuously compared with the contract meteorological predictions.
3. Reports from Neighboring Electrical Companies Telephone communication with other electrical companies often provides useful additional information on weather conditions, etc.

### Load Prediction and "Model Weather Day"

Having obtained a weather prediction, the dispatcher searches recent weather records for a day with meteorological conditions similar to those predicted for his planning period. He can then use the loads that actually occurred on this "model day" as a guideline for current load predictions. Naturally, a close watch is kept on weather conditions, since a sudden change could warrant a shift to a new model day. It is not unusual for model days to change three or four times during a twenty-four hour period, due to unforeseen meteorological conditions.

For prediction purposes, each twenty-four hour day is divided into approximately two planning horizons; one covering each of the morning and evening peak loads. It is the responsibility of the night dispatcher to schedule equipment onto the system for the morning peak, and of the day dispatcher to set the system up for the anticipated evening load.

### Load Prediction and Equipment Selection

Once the load prediction is made, the dispatcher must allocate this demand to the various generating units in the system. The availability and capacity of different units will change from day to day due to planned maintenance on certain units, unexpected equipment outages, steam regeneration problems, etc. The load dispatcher receives a daily report from each plant regarding the expected condition of the generating units for the time period of the dispatching decision.

After the status of equipment is reported, the dispatcher seeks to satisfy the load prediction of the day using the most economically efficient units available. A list is prepared which relates the available units to their economic efficiency. The units are listed in order of most to least efficient using an incremental cost per kilowatt hour as the index of efficiency for each unit. The incremental cost is calculated for each unit at the most efficient operating load level. This is ordinarily at or near unit capacity.

The number of units to be put on line that day is determined by noting the peak load expected and then selecting units from the unit efficiency list according to minimum incremental cost until that peak capacity is met. A spinning reserve of some 300 megawatts is kept on line for contingencies. Since peak loads do not occur until later in the day, the full capacity is not put on line immediately. The dispatcher generates a schedule for the units so that programmed increases in unit capacity will correspond to his load curve for the day.

Included in his operating plan is the possibility of buying or selling electricity from neighboring companies. That is, when the price of purchased electricity is less than the cost of adding a unit, the dispatcher will "shop around" among his neighbors to buy the required amount of power at the least possible price. Similarly, he may be called upon to "sell" electricity if it is available in the system. Thus, the ability to purchase electricity is analogous to having an additional unit in the system whose capacity and cost are continuously varying.

## System Operation

After preparing the system operating plan for his planning horizon, the dispatcher informs the plants of their load schedules (i.e., when they are to have certain units ready to bring onto the system and to what capacity); he then begins the task of monitoring the system's operation.

Although the major equipment decision for the twelve hour period is made, the network is constantly subject to smaller scale demand perturbations which require continuous monitoring of the output of each unit. The committed units were selected on the basis of their peak efficiency. Because of these small demand perturbations, however, the units cannot be run at peak efficiency at all times, but must vary their output according to the instantaneous demands of the system. The monitoring function then seeks an instantaneous response to demand perturbation by continuous control of the actual power generation from the units.

Assisting the dispatcher in this task is the automatic dispatch system (ADS). This is an electronic analog device which has the operating characteristics of each unit built into its controlling mechanism. The ADS system seeks to control the committed, on-line units so that electricity is being produced as economically as possible at any instant in time. It accomplishes this by automatically opening and closing "valves" on the units. Opening a valve causes an increase in the energy input to the unit resulting in a higher electrical

output. Each unit has several valves and associated with each valve is an incremental cost of producing electricity which depends on the operating level of the unit. Each valve incremental cost may be regarded as a point on a cost versus load curve for each unit. The ADS system has this information built into its controls and when demand on the system increases, ADS automatically opens the next most efficient valve.

The dispatcher follows the operation of the ADS system by preparing a "system operating guide." This is a list of all valves ordered by increasing incremental cost regardless of the unit to which the valve corresponds. By knowing what the current incremental cost of generating power is, the dispatcher knows which valves are open.

The dispatcher continually monitors the operation of the system via a control panel which contains several strip chart recorders. The control panel provides such information as the total system load in megawatts, the current incremental cost of producing electricity in mils per kilowatt, the individual plant loads, and the amount of electricity flowing into (or out of) the system from neighboring companies.

#### 6.4.3 Feasibility of Control

Having analyzed CECO's electrical production control system, it is necessary to seek a method of perturbing this system for the purposes of air pollution abatement. To accomplish this, it is necessary to determine:

1. What types of control are feasible and how readily can they be applied;
2. What are the economic and physical consequences of applying feasible controls; and
3. What are the economic and physical constraints associated with the application of feasible controls.

#### Control by Load Reduction

CECO is constrained to meet the total load demand on its system. There is, however, a wide choice in the way this demand is met, if the system is not being operated at capacity. Thus, load reduction at one plant or even a number of plants is usually feasible by shifting the power demand to other plants in the system.

As discussed above, CECO's equipment selection rules are largely economic in nature, although occasional equipment outages may necessitate temporary deviations from such rules. Such deviations are somewhat analogous to the imposition of air pollution constraints on the operating system - they may cause CECO to deviate from an otherwise economically optimal operating procedure for a short period of time. CECO's general solution to temporary equipment outages is to have enough "slack" in the system to shift load to another plant. Although such a shift increases the cost of producing electricity, the increase incurred for a small load shift from a temporarily polluted area may not be excessively disruptive. Thus, load shifting within the physical limits of the CECO system for the abatement of "localized" incidents may be a highly desirable control mechanism.

The amount of power that can be shifted at any time depends on the plant involved, the status of the system, and the nature of the load curve as shown in Figure 6.3. Load shifting is difficult to accomplish when the system is near peak or minimum load (Periods 2, 4 and 6).

For widespread (i.e., city wide) pollution incidents, power shifting out of the city (and indeed out of the system) may be necessary. Although a large shift is certainly more costly and more difficult to accomplish, the prospects of purchasing power from neighboring companies may become attractive under aggravated air pollution conditions. In the future, it may be possible to form reciprocal agreements to obtain "pollution abatement" power from neighbor companies during a pollution incident and return this borrowed power at some later date.

#### Control by Fuel Switching

On the average, a large percentage (about two-thirds) of CECO's urban capacity could be produced by natural gas if this fuel were available. This is, in fact, the case during the summer when CECO burns mostly gas which is available at "dump rates." During the winter, however, gas is usually available only at premium rates.

Many units of the urban network are capable of burning gas in combination with coal, and some can generate entirely on gas. For those units which are equipped to burn gas, nearly any combination of coal and gas is possible. The gas company provides CECO with a thirty minute advance notice when gas can be made available and at what plants. The dispatcher then informs the affected plants which units are to engage in a fuel switch.

CECO has purchased a block of gas which may be used during the heating season in the event of a pollution incident. This winter gas is relatively expensive and the supply is limited. A severe cost penalty is assessed if the contract limit is exceeded. The availability of this "pollution gas" is also limited with regard to hourly delivery rate. The latter is dependent on temperature (i.e., the lower the temperature, the less the delivery rate in therms per hour). These limitations obviously imply the judicious use of this gas. However, since CECO has purchased and agreed to burn this gas during the winter season, if the end of the season is approaching and the gas has not been used, it becomes increasingly desirable to expend it.

#### Combining Fuel Switching and Load Reduction

It is evident from the above discussion that a combination of fuel switching and load shifting is a possible air pollution abatement technique. Since pollution gas is relatively expensive to use, a feasible strategy which satisfies the pollution constraints would first shift power within the physical limitations of the system. If load shifting does not produce an acceptable air quality condition, then pollution gas must be used for minimal operational and economic disruption. Power shifting and gas usage should be minimized. The attainment of this objective is the purpose of the control model which was developed during this pilot study. The model is described in the next section.

#### 4.4 Formulation of the Mathematical Control Model

The discussion in Section 6.4.3 has served to identify the essential components of an optimal emission control model. These components are:

- 1) The planning horizon - the predicted length of the pollution incident in hours;
- 2) The variables which can be manipulated for control purposes - the hourly amount of gas burned (in therms) and the hourly amount of load shifted (in megawatts) for each unit;
- 3) The objective - to minimize the hourly gas usage and load shift for each unit;
- 4) The constraining relationship which limit the values the control variables may assume - the maximum allowable hourly pollution concentration (in ppm) measured at each TAM station, and the maximum feasible hourly gas usage and load shift for each unit.

This problem must now be translated into symbols so that a mathematical solution technique can be applied. To simplify the formulation of the problem, the mathematical statement of the control model described here will be limited to a planning horizon of two hours and a two plant (i.e., two unit), two receptor system. The extension to the general case is quite straightforward, as will be seen later. This extension was made and implemented for a three plant-two receptor system with an extended time horizon. The simplified model described below is provided solely for explanatory purposes.

The indices needed to formulate the control model are:

- 1) an hour index  $t$  ( $t = 1, 2$ );
- 2) a unit index  $j$  ( $j = 1, 2$ ); and
- 3) a receptor index  $i$  ( $i = 1, 2$ ).

For this formulation:  $j = 1$  is the Fisk plant;

$j = 2$  is the Crawford plant;

$i = 1$  is the Lindbloom receptor; and

$i = 2$  is the Hyde Park receptor.

### The Control Variables

Let the amount of gas burned in unit  $j$  during hour  $t$  be  $G_j(t)$  and the amount of electricity produced by  $D_j(t)$ . Also, let  $U_j(t)$  be the load on unit  $j$  in hour  $t$  predicted by the load dispatcher. Then the total load shift is given by

$$Y_j(t) = U_j(t) - D_j(t). \quad (1)$$

Thus, the control variables are

$$G_1(1), Y_1(1), G_2(1), Y_2(1), G_1(2), Y_1(2), G_2(2), Y_2(2).$$

### The Objective Function

As stated earlier, the most economically attractive type of control is a load shift from the units contributing to high pollution levels. In applying this control, however, the objective is to shift only what is necessary to reduce the pollution to an acceptable level. Let  $d_j(t)$  be the cost (or "penalty") per megawatt of deviation from the predicted load,  $U_j(t)$  for unit  $j$  during hour  $t$ . Then  $d_j(t)Y_j(t)$  is the

total cost incurred by the company during hour  $t$  for a shift of  $Y_j(t)$  megawatts from unit  $j$ . The objective is to minimize this quantity for all hours of the incident and each unit  $j$ . Thus, it is necessary to minimize

$$Z_1 = d_1(1)Y_1(1) + d_2(1)Y_2(1) + d_1(2)Y_1(2) + d_2(2)Y_1(1). \quad (2)$$

Each unit has a minimum operating level which depends on time. If this is denoted by  $L_j(t)$ , the maximum load shift,  $\bar{Y}_j(t)$  is given by

$$\bar{Y}_j(t) = U_j(t) - L_j(t), \quad \begin{matrix} j = 1, 2 \\ t = 1, 2. \end{matrix} \quad (3)$$

Thus, if all units in the system are operating at their minimum levels and the pollution reading at some receptor is still above an acceptable level, some gas must be used to reduce it. The objective here is to use only as much gas as is needed to accomplish the required reduction. If  $g_j$  denotes the cost per therm of burning gas in unit  $j$ , and  $c_j$  is the cost of burning coal, the total cost incurred by the company for burning  $G_j(t)$  therms of gas during hour  $t$  in unit  $j$  is  $(g_j - c_j)G_j(t)$ . Again, the objective is to minimize this quantity for all hours of the incident and each unit  $j$ . Thus, it is necessary to minimize

$$\begin{aligned} Z_2 = & (g_1 - c_1)G_1(1) + (g_2 - c_2)G_2(1) \\ & + (g_1 - c_1)G_1(2) + (g_2 - c_2)G_2(2). \end{aligned} \quad (4)$$

Finally combining both types of control, the objective is to minimize

$$Z = Z_1 + Z_2. \quad (5)$$

A difficulty associated with the direct use of this objective function is the assignment of values to  $d_j(t)$  - a result of the complexity of CECO's cost allocation system. However, a simplified objective function can be formulated which circumvents this problem. Since the differential cost of burning gas is relatively constant between units and the amount of load shifted from one or two units will produce only microscopic changes in the total system operating cost, the fuel differential cost weights of (4) can be dropped and the objective function can be simplified to minimize

$$Z = G_1(1) + G_2(1) + G_1(2) + G_2(2) \\ + Y_1(1) + Y_2(1) + Y_1(2) + Y_2(2). \quad (6)$$

The only difference between (5) and (6) is that Eq. 6 does not discriminate between units on a differential fuel cost basis. This is acceptable to CECO, however, for this is exactly what they are equipped to do via the ADS system mentioned earlier. This objective function will seek to impose controls on unit  $j$  solely on the basis of its contribution to the pollution level at each receptor during the incident.

#### The Constraints

A basic assumption of the DAVKERN  $SO_2$  dispersion model (see ANL-ES-CC-002) and most other air quality prediction schemes is that of source superposition. That is, the contribution from individual sources to the air quality sensed by particular receptor can be arithmetically summed to yield the total pollution concentration at that receptor.

If  $Q_j(\tau)$  denotes the emission from source  $j$  during hour  $\tau$  and  $\alpha_{ij}(t - \tau + 1)$  is the fraction of the pollutant emitted  $\tau$  hours ago that is "received" at receptor  $i$  during hour  $t$ , then the total contribution to the receptor reading is  $\alpha_{ij}(t - \tau + 1)Q_j(\tau)$ . For this control model, the coefficients  $\alpha_{ij}(t - \tau + 1)$  are calculated by the DAVKERN "integrated puff" physical prediction model.\* These coefficients are normalized so that the calculated receptor contributions are measured in ppm. By superposition, the total receptor value during hour  $t$  is obtained by summing the contributions from all units  $j$  and all previous hours  $\tau$ . For each hour during the incident and each receptor, these values are constrained to be less than a prescribed value, say  $p$  ppm. Thus, for the simplified system under consideration, the following four "pollution" constraining relationships must hold.

$$\begin{aligned}
 (i = 1, t = 1) \quad & \alpha_{11}(1)Q_1(1) + \alpha_{12}(1)Q_2(1) \leq P \\
 (i = 2, t = 1) \quad & \alpha_{21}(1)Q_1(1) + \alpha_{22}(1)Q_2(1) \leq P \\
 (i = 1, t = 2) \quad & \alpha_{11}(2)Q_1(1) + \alpha_{12}(2)Q_2(1) \\
 & + \alpha_{11}(1)Q_1(2) + \alpha_{12}(1)Q_2(2) \leq P \\
 (i = 2, t = 2) \quad & \alpha_{21}(2)Q_1(1) + \alpha_{22}(2)Q_2(1) \\
 & + \alpha_{21}(1)Q_1(2) + \alpha_{22}(1)Q_2(2) \leq P.
 \end{aligned} \tag{7}$$

These constraints have been written in terms of  $SO_2$  emitted, and not in terms of the original control variables,  $G_j(t)$  and  $Y_j(t)$ . To

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\*The constraining relationships developed in this section will apply to any predictive model for which the assumption of superposition of sources is retained.

accomplish this substitution, it may be noted that the thermal input of coal to unit  $j$  during hour  $t$  [denoted by  $C_j(t)$ ] is proportional to the emission  $Q_j(t)$ . Thus, assuming that this proportionality constant is incorporated into the normalization of the coupling coefficients, the constraints can be rewritten with the  $C_j(t)$  replacing the  $Q_j(t)$ . Now letting  $T_j(t)$  denote the total thermal input to unit  $J$  in hour  $t$ , and assuming that only gas or coal or a combination of both is burned, the total thermal input becomes the sum of the coal input and gas input.

Thus

$$T_j(t) = C_j(t) + G_j(t)$$

or

$$C_j(t) = T_j(t) - G_j(t). \quad (8)$$

Now the total thermal input is a function of the load on the unit. That is

$$T_j(t) = F_j[D_j(t)] = F_j[U_j(t) - Y_j(t)] = F_j[Y_j(t)]. \quad (9)$$

Finally, the required substitution becomes

$$C_j(t) = F_j[Y_j(t)] - G_j(t). \quad (10)$$

The pollution constraints now become

$$\begin{aligned} (i = 1, t = 1) \quad & \alpha_{11}(1) \langle F_1[Y_1(1)] - G_1(1) \rangle \\ & + \alpha_{12}(1) \langle F_2[Y_2(1)] - G_2(1) \rangle \leq P \\ (i = 2, t = 1) \quad & \alpha_{21}(1) \langle F_1[Y_1(1)] - G_1(1) \rangle \\ & + \alpha_{22}(1) \langle F_2[Y_2(1)] - G_2(1) \rangle \leq P \end{aligned} \quad (11)$$

NOTE: (Equation 11 is continued on next page).

$$\begin{aligned}
(i = 1, t = 2) \quad & \alpha_{11}^{(2)} \langle F_1[Y_1(1)] - G_1(1) \rangle \\
& + \alpha_{12}^{(2)} \langle F_2[Y_2(1)] - G_2(1) \rangle \\
& + \alpha_{11}^{(1)} \langle F_1[Y_1(2)] - G_1(2) \rangle \\
& + \alpha_{12}^{(1)} \langle F_2[Y_2(2)] - G_2(2) \rangle \leq P \\
(i = 2, t = 2) \quad & \alpha_{21}^{(2)} \langle F_1[Y_1(1)] - G_1(1) \rangle \\
& + \alpha_{22}^{(2)} \langle F_2[Y_2(1)] - G_2(1) \rangle \\
& + \alpha_{21}^{(1)} \langle F_1[Y_1(2)] - G_1(2) \rangle \\
& + \alpha_{22}^{(1)} \langle F_2[Y_2(2)] - G_2(2) \rangle \leq P.
\end{aligned} \tag{11}$$

As mentioned above, the amount of load shift is limited by  $U_j(t) - L_j(t)$ .

That is

$$0 \leq Y_j(t) \leq \bar{Y}_j(t) = U_j(t) - L_j(t), \quad \begin{matrix} j = 1, 2 \\ t = 1, 2. \end{matrix} \tag{12}$$

The maximum hourly thermal delivery of gas to each plant has been negotiated between CECO and the gas company. If this amount is denoted by  $\bar{G}_j(t)$ , the gas usage constraints become

$$0 \leq G_j(t) \leq \bar{G}_j(t), \quad \begin{matrix} j = 1, 2 \\ t = 1, 2. \end{matrix} \tag{13}$$

The complete mathematical form of the problem can now be stated. The objective is to minimize

$$Z = G_1(1) + G_2(1) + G_1(2) + G_2(2) + Y_1(1) + Y_2(1) + Y_1(2) + Y_2(2)$$

subject to the constraints

1) Pollution

$$(i = 1, t = 1) \quad \alpha_{11}(1) \langle F_1[Y_1(1)] - G_1(1) \rangle \\ + \alpha_{12}(1) \langle F_2[Y_2(1)] - G_2(1) \rangle \leq P$$

$$(i = 2, t = 1) \quad \alpha_{21}(1) \langle F_1[Y_1(1)] - G_1(1) \rangle \\ + \alpha_{22}(1) \langle F_2[Y_2(1)] - G_2(1) \rangle \leq P$$

$$(i = 1, t = 2) \quad \alpha_{11}(2) \langle F_1[Y_1(1)] - G_1(1) \rangle \\ + \alpha_{12}(2) \langle F_2[Y_2(1)] - G_2(1) \rangle \\ + \alpha_{11}(1) \langle F_1[Y_1(2)] - G_1(2) \rangle \\ + \alpha_{12}(1) \langle F_2[Y_2(2)] - G_2(2) \rangle \leq P$$

$$(i = 2, t = 2) \quad \alpha_{21}(2) \langle F_1[Y_1(1)] - G_1(1) \rangle \\ + \alpha_{22}(2) \langle F_2[Y_2(1)] - G_2(1) \rangle \\ + \alpha_{21}(1) \langle F_1[Y_1(2)] - G_1(2) \rangle \\ + \alpha_{22}(1) \langle F_2[Y_2(2)] - G_2(2) \rangle \leq P, \quad (14)$$

2) Gas usage

$$0 \leq G_j(t) \leq \bar{G}_j(t), \quad \begin{matrix} j = 1, 2 \\ t = 1, 2, \end{matrix}$$

3) Load Shift

$$0 \leq Y_j(t) \leq \bar{Y}_j(t) = U_j(t) - L_j(t) \quad \begin{matrix} j = 1, 2 \\ t = 1, 2. \end{matrix}$$

The extension of the above to a general model is now quite straightforward. If  $T$  denotes the length of the incident,  $J$  the number of units, and  $I$  the number of receptors, the general formulation is

$$\text{minimize } Z = \sum_{j=1}^J \sum_{t=1}^T G_j(t) + Y_j(t), \quad \begin{matrix} j = 1, 2, \dots, J \\ t = 1, 2, \dots, T, \end{matrix}$$

subject to the constraints

1) Pollution

$$\sum_{j=1}^J \sum_{\tau=1}^t \alpha_{ij} (t - \tau + 1) \{F_j[Y_j(\tau)] - G_j(\tau)\} \leq P, \quad \begin{matrix} i = 1, 2, \dots, I \\ t = 1, 2, \dots, T, \end{matrix}$$

2) Gas usage

$$0 \leq G_j(t) \leq \bar{G}_1(t), \quad \begin{matrix} j = 1, 2, \dots, J \\ t = 1, 2, \dots, T \end{matrix}$$

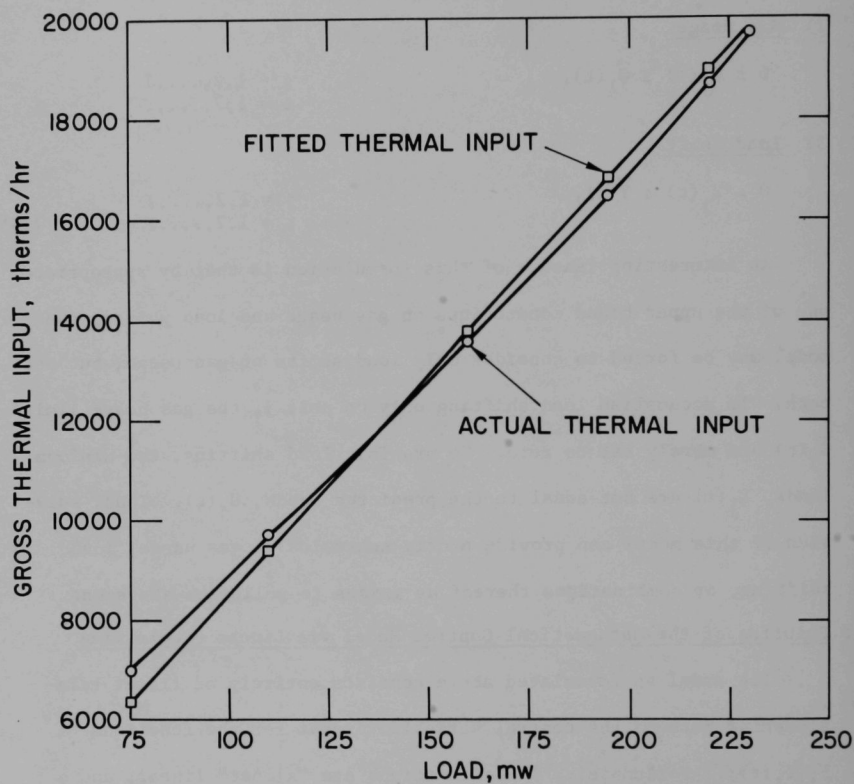
3) Load shift

$$0 \leq Y_j(t) \leq \bar{Y}(t), \quad \begin{matrix} j = 1, 2, \dots, J \\ t = 1, 2, \dots, T \end{matrix} \quad (15)$$

An interesting feature of this formulation is that by appropriate use of the upper bound constraints on gas usage and load shifts, the model may be forced to consider only load shifts or gas usage, but not both. To accomplish load shifting only on unit  $j$ , the gas usage limits  $\bar{G}_j(t)$  are merely set to zero. To prohibit load shifting, the minimum loads,  $L_j(t)$  are set equal to the predicted loads,  $U_j(t)$ . Thus, solution of this model can provide hourly schedules of gas usage, load shifting, or combinations thereof as guides to pollution abatement.

4.5 Solution of the Mathematical Control Model via Linear Programming

The model as formulated above consists entirely of linear relationships between the control variables except for the functions  $F_j[Y_j(t)]$ . Fortunately, these functions are "almost" linear, and a least squares linear fit yields errors of less than 5% over most of the unit operating ranges. Figure 6.5 shows a typical gross thermal input vs. load curve and the approximating straight line.



112-9796

Fig. 6.5 Typical Gross Thermal Input vs. Load Curve and Least Squares Approximating Line

Thus, we have

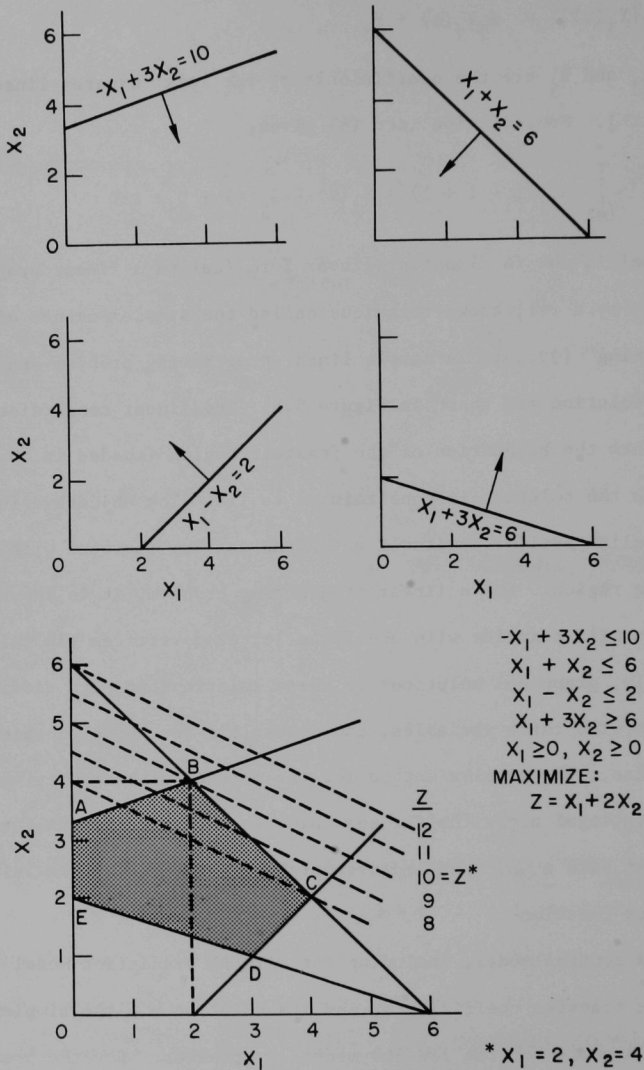
$$F_j[Y_j(t)] = A_j Y_j(t) + B_j \quad (17)$$

where  $A_j$  and  $B_j$  are the coefficients of the least squares linear fit for unit  $j$ . Substitution into (6) gives,

$$\sum_{j=1}^J \sum_{\tau=1}^t \alpha_{ij} (t - \tau + 1) \{A_j Y_j(\tau) - G_j(\tau) + B_j\} \leq P \quad (18)$$

The model is now in classical linear form (called a linear program) for solution by a well known technique called the simplex method of "linear programming" [17,18]. A sample linear programming problem and its graphical solution are shown in Figure 6.6. The linear constraint relationships form the boundaries of the feasible region (shaded in the figure) in which the solution is constrained to lie. The objective function  $Z$  can be slid parallel to itself until the maximum is found within the feasible region. For a linear programming problem, it is known that the solution will coincide with one of the lettered vertices (in this case B). Obviously, graphical solutions of these relationships are difficult for problems with three variables, and impossible for those containing more than three. The simplex method for the general problem of  $n$  variables is a computational algorithm for searching the vertices of the feasible region in such a way that improvement is always made in the value of the objective function.

The control model, including the DAVKERN prediction model to calculate the transfer coefficients, and its solution via the simplex method have been coded for the IBM 360 model 75 computer. For the present



112-9797

Fig. 6.6 Graphical Solution of a Linear Programming Problem

demonstration, the code considers only a six hour control period, but it can be extended easily. The limitations on the use of this system for advance control are, of course, imposed entirely by the meteorological ability to produce accurate advance forecasts.

Sample runs are exhibited in Tables 6.1 and 6.2. The inputs to the program are simply predicted weather parameters, the dispatcher's predicted hourly load schedule,  $U_j(t)$ , and the hourly minimum loads,  $L_j(t)$ . The program will then compute the gas usage,  $G_j(t)$ , and unit load shifts,  $Y_j(\tau)$ , which satisfy the pollution constraints and minimize the objectives.

Desirable features of the program are:

- 1) It is flexible - takes account of CECO's daily operational and economic situation;
- 2) It is specific to the control of each different predicted incident;
- 3) It is adaptive - the program can easily be rerun if weather conditions change.

Experiments in implementing this program on teleprocessing equipment are currently being conducted. If the use of such equipment is feasible, a terminal could be installed in the CECO dispatching center or in the air pollution control department and linked to a computing facility, where the prediction and control code would be stored. Weather forecasts and predicted power demands could be typed into the teleprocessing console when a dispersion prediction model indicated excessively high concentrations that were expected. An optimal emission control program would

Table 6.1 Optimal Emission Control Strategy-Typical Computer Output

RUN 1 WS = 2 MPH GAS USAGE ONLY													
HOUR	FISK 18		FISK 19		CRAWFORD 6		CRAWFORD 7		CRAWFORD 8		POLLUTION LINDBLOM	LEVELS (ppm) HYDE PARK	
	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD			
4	0.0	0.0	210.0	210.0	0.0	0.0	153.0	153.0	268.0	268.0	0.000	0.0000	
5	0.0	0.0	240.0	240.0	0.0	0.0	177.0	177.0	298.0	298.0	0.199	0.0068	
6	0.0	0.0	282.0	282.0	0.0	0.0	178.0	178.0	304.0	304.0	0.603	0.0820	
7	26.0	26.0	310.0	310.0	0.0	0.0	210.0	210.0	331.0	331.0	0.692	0.2290	
8	87.0	87.0	323.0	323.0	0.0	0.0	219.0	219.0	353.0	353.0	0.734	0.3170	
9	145.0	145.0	330.0	330.0	55.0	55.0	212.0	212.0	360.0	360.0	0.804	0.3710	
RUN 2 WS = 2 MPH GAS USAGE AND LOAD SHIFT													
HOUR	FISK 18		FISK 19		CRAWFORD 6		CRAWFORD 7		CRAWFORD 8		POLLUTION LINDBLOM	LEVELS (ppm) HYDE PARK	
	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD			
4	0.0	0.0	210.0	175.0	0.0	0.0	153.0	125.0	268.0	130.0			
5	0.0	0.0	240.0	175.0	0.0	0.0	177.0	125.0	298.0	130.0			
6	0.0	0.0	282.0	175.0	0.0	0.0	178.0	125.0	304.0	130.0			
7	26.0	26.0	310.0	175.0	0.0	0.0	210.0	125.0	331.0	130.0	SAME AS ABOVE		
8	87.0	40.0	323.0	175.0	0.0	0.0	219.0	125.0	353.0	130.0			
9	145.0	40.0	330.0	175.0	55.0	30.0	212.0	150.0	360.0	150.0			
RUN 3 WS = 4 MPH GAS USAGE ONLY													
HOUR	FISK 18		FISK 19		CRAWFORD 6		CRAWFORD 7		CRAWFORD 8		POLLUTION LINDBLOM	LEVELS (ppm) HYDE PARK	
	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD			
4	0.0	0.0	210.0	210.0	0.0	0.0	153.0	153.0	268.0	268.0	0.036	0.0000	
5	0.0	0.0	240.0	240.0	0.0	0.0	177.0	177.0	298.0	298.0	0.216	0.0170	
6	0.0	0.0	282.0	282.0	0.0	0.0	178.0	178.0	304.0	304.0	0.240	0.0210	
7	26.0	26.0	310.0	310.0	0.0	0.0	210.0	210.0	331.0	331.0	0.248	0.0240	
8	87.0	87.0	323.0	323.0	0.0	0.0	219.0	219.0	353.0	353.0	0.276	0.0280	
9	145.0	145.0	330.0	330.0	55.0	55.0	212.0	212.0	360.0	360.0	0.297	0.0340	
HOUR	FISK 18		FISK 19		CRAWFORD 6		CRAWFORD 7		CRAWFORD 8		POLLUTION LINDBLOM	LEVELS (ppm) HYDE PARK	
	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD	PRED LOAD	MIN LOAD			
4	0.0	0.0	210.0	210.0	0.0	0.0	153.0	125.0	268.0	130.0			
5	0.0	0.0	240.0	240.0	0.0	0.0	177.0	125.0	298.0	130.0			
6	0.0	0.0	282.0	282.0	0.0	0.0	178.0	125.0	304.0	130.0			
7	26.0	26.0	310.0	310.0	0.0	0.0	210.0	125.0	331.0	130.0	SAME AS ABOVE		
8	87.0	87.0	323.0	323.0	0.0	0.0	219.0	125.0	353.0	130.0			
9	145.0	145.0	330.0	330.0	55.0	30.0	212.0	150.0	360.0	150.0			

PREDICTED AND MINIMUM LOADS AND RESULTING POLLUTION LEVELS WITHOUT ABATEMENT PROGRAMS.

Table 6.2 Optimal Emission Control Strategy-Typical Computer Output

RUN 1 WS = 2 MPH GAS USAGE ONLY												
HOUR	FISK 18		FISK 19		CRAWFORD 6		CRAWFORD 7		CRAWFORD 8		POLLUTION LINDBLUM	LEVELS (ppm) HYDE PARK
	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)		
4	C.O	0.0	C.O	210.0	0.0	0.0	13102.2	153.0	12442.0	268.0	0.000	0.0000
5	C.O	0.0	C.O	240.0	0.0	0.0	15171.3	177.0	6422.1	298.0	0.052	0.0068
6	C.O	0.0	5830.3	282.0	0.0	0.0	15257.5	178.0	24701.3	304.0	0.260	0.0750
7	2499.5	26.0	787.3	310.0	0.0	0.0	18016.3	210.0	26905.1	331.0	0.200	0.1650
8	C.O	87.0	C.O	323.0	0.0	0.0	12140.3	219.0	0.0	353.0	0.015	0.2000
9	C.O	145.0	C.O	330.0	0.0	55.0	0.0	212.0	0.0	360.0	0.200	0.2000
RUN 2 WS = 2 MPH GAS USAGE AND LOAD SHIFT												
HOUR	FISK 18		FISK 19		CRAWFORD 6		CRAWFORD 7		CRAWFORD 8		POLLUTION LINDBLUM	LEVELS (ppm) HYDE PARK
	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)		
4	C.O	0.0	C.O	175.0	0.0	0.0	7673.1	125.0	0.0	130.0	0.000	0.0000
5	C.O	0.0	C.O	175.0	0.0	0.0	10688.3	125.0	697.5	130.0	0.076	0.0056
6	C.O	0.0	C.O	175.0	0.0	0.0	6736.3	125.0	0.0	130.0	0.200	0.0630
7	C.O	26.0	C.O	196.5	0.0	0.0	10688.3	125.0	4396.1	130.0	0.200	0.1400
8	C.O	87.0	C.O	323.0	0.0	0.0	0.0	125.0	0.0	130.0	0.200	0.1590
9	C.O	145.0	C.O	330.0	0.0	55.0	0.0	212.0	0.0	360.0	0.200	0.1850
RUN 3 WS = 4 MPH GAS USAGE ONLY												
HOUR	FISK 18		FISK 19		CRAWFORD 6		CRAWFORD 7		CRAWFORD 8		POLLUTION LINDBLUM	LEVELS (ppm) HYDE PARK
	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)		
4	C.O	0.0	C.O	210.0	0.0	0.0	1900.0	153.0	0.0	268.0	0.034	0.0000
5	C.O	0.0	C.O	240.0	0.0	0.0	6369.0	177.0	0.0	298.0	0.200	0.0170
6	C.O	0.0	C.O	282.0	0.0	0.0	7180.8	178.0	0.0	304.0	0.200	0.0200
7	C.O	26.0	C.O	310.0	0.0	0.0	11001.6	210.0	0.0	331.0	0.200	0.0270
8	C.O	87.0	C.O	323.0	0.0	0.0	18792.2	219.0	304.9	353.0	0.200	0.0280
9	C.O	145.0	C.O	330.0	0.0	55.0	0.0	212.0	0.0	360.0	0.200	0.0320
RUN 4 WS = 4 MPH GAS USAGE AND LOAD SHIFT												
HOUR	FISK 18		FISK 19		CRAWFORD 6		CRAWFORD 7		CRAWFORD 8		POLLUTION LINDBLUM	LEVELS (ppm) HYDE PARK
	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)	GAS (THMS)	LOAD (MGW)		
4	C.O	0.0	C.O	210.0	0.0	0.0	0.0	131.0	0.0	268.0	0.034	0.0000
5	C.O	0.0	C.O	240.0	0.0	0.0	0.0	125.0	0.0	274.9	0.200	0.0160
6	C.O	0.0	C.O	282.0	0.0	0.0	0.0	125.0	0.0	272.0	0.200	0.0200
7	C.O	26.0	C.O	310.0	0.0	0.0	0.0	125.0	0.0	286.0	0.200	0.0230
8	C.O	87.0	C.O	323.0	0.0	0.0	0.0	125.0	0.0	218.3	0.200	0.0270
9	C.O	145.0	C.O	330.0	0.0	55.0	0.0	212.0	0.0	360.0	0.200	0.0320

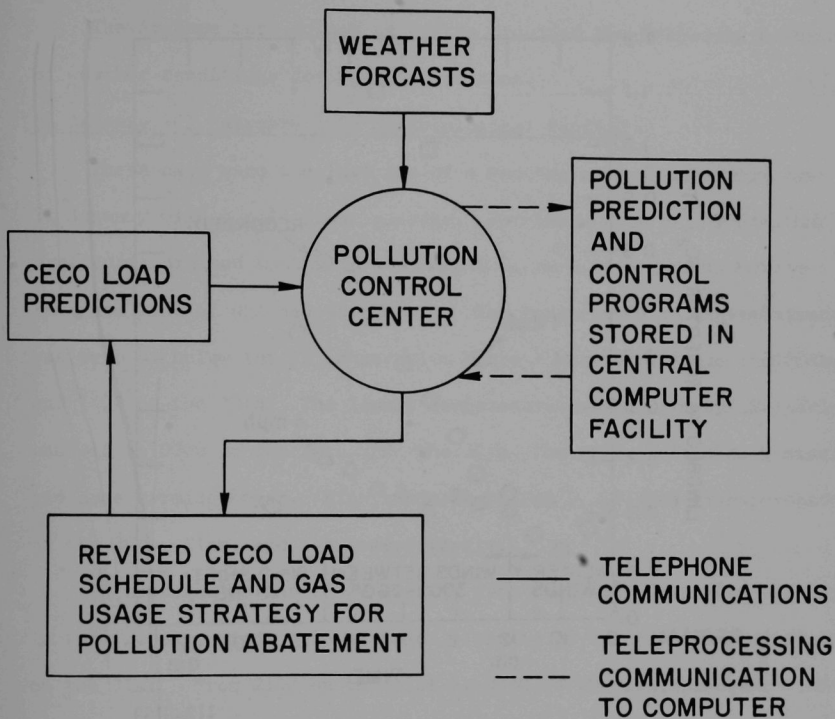
GAS USAGE, LOADS, AND RESULTING POLLUTION LEVELS USING ABATEMENT PROGRAMS.

immediately be computed and returned. Required access to the computer would be sporadic and of short duration, but near real time response would be desired. Thus, a high priority would have to be given pollution control requests if such a system is to be operationally successful. A schematic diagram of the operation of such a real time pollution control system is shown in Figure 6.7.

#### 6.4.6 Discussion of Results and Model Validity

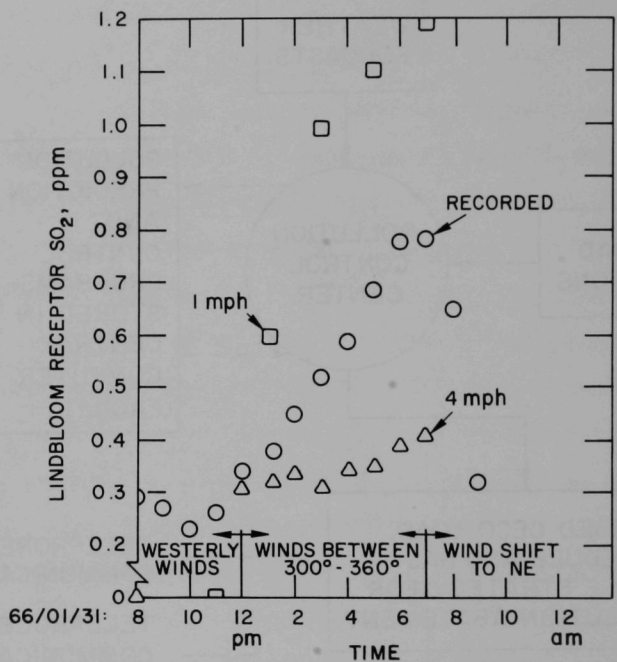
Once the control model had been developed, a search was made for a realistic test of its validity. Since the diffusion analysis studies indicate that the Hyde Park area is highly "self-polluting," the search centered about the Lindbloom receptor. The master data program was instructed to search the 1966-67 Lindbloom air quality records for pollution concentrations in excess of .2 ppm and low wind speeds between 270 and 360 degrees. Three "incidents" (of duration 12 hours or more) were found, and one which looked as though the Crawford plant might be a major contributor was chosen as the sample test case. The test incident began on January 31, 1966, at 8 a.m. the following day when a wind change caused the ambient pollution level to drop. The  $\text{SO}_2$  levels actually recorded at the Lindbloom station are shown in Figure 6.8.

A statistical analysis using Crawford  $\text{SO}_2$  emission data and temperature as independent variables indicated that Crawford's contribution to the air quality monitored at the Lindbloom receptor during this time was significantly different from zero at the .97 confidence level. It should be emphasized that this finding was used only as an indication



112-9798

Fig. 6.7 Teleprocessing Control System Schematic



112-9799

Fig. 6.8 Predicted and Measured Air Quality at Lindbloom Receptor During Test Incident

that Crawford did contribute to this incident in order to obtain realistic data for testing the control model. It cannot be used as proof of Crawford's culpability due to the small data sample size and the absence of data which would resolve the contributions of other possible sources. "Incident analysis," as such, was not within the scope of this study.

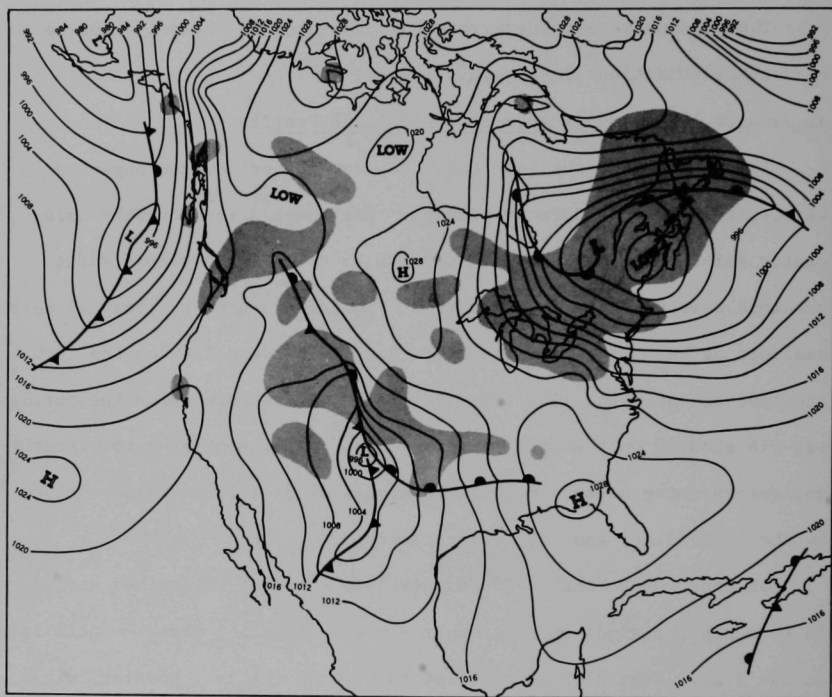
The Argonne meteorology group has provided the following analysis of weather conditions during this incident.

#### 31 January - 1 February 1966 Meteorological Profile

These days were the last two of a weather period that began on 21 January with a cold front passage. For three days extremely cold arctic air drained southward into the U.S. as a high pressure ridge remained west of Chicago (Fig. 6.9). The temperature at Midway Airport was zero or below for 72 consecutive hours - between 1500 on the 27th and 1400 on the 30th. The lowest temperature reached during the period was -16 at 0700 on the 29th. On the 30th, the wind shifted to westerly and some warming began. High temperatures of 3, 17, and 29 were reached on the 30th, 31st, and 1st, respectively.

In contrast to the 19-20 January 1966 incident, described earlier in this report, winds were stronger - mostly 10 kt or above - until late on the 31st. From 2100 on the 31st to 0900 on the 1st, however, winds were mostly 5 kt or less.

Skies were partly cloudy to overcast during much of the period. The only long period of clear skies occurred between 0000 on the 30th and 1100 on the 31st.



113-1100

Fig. 6.9 Surface Weather Map, 1200 CST Jan. 31, 1966

These clear skies account for the radiation inversion observed on the 0600 temperature soundings at Peoria and Green Bay. In Figure 6.10, a Chicago rural temperature sounding was constructed from the Chicago rural (Argonne) 0600 temperature and the average slopes of individual segments of the Peoria and Green Bay temperature profiles. The mixing depth was estimated as the height above the surface where the dry adiabat from the 0600 Midway (city) temperature intersects the Chicago rural sounding. The estimated mixing depth is 180 m (590 ft).<sup>\*</sup> The constructed Chicago sounding is colder at about 960 mb than both Green Bay and Peoria. This temperature estimate is probably too low--the actual temperature is probably intermediate between the Green Bay and Peoria temperatures. This means that the estimated mixing depths probably errs on the side of being too high, by 40-50 m.

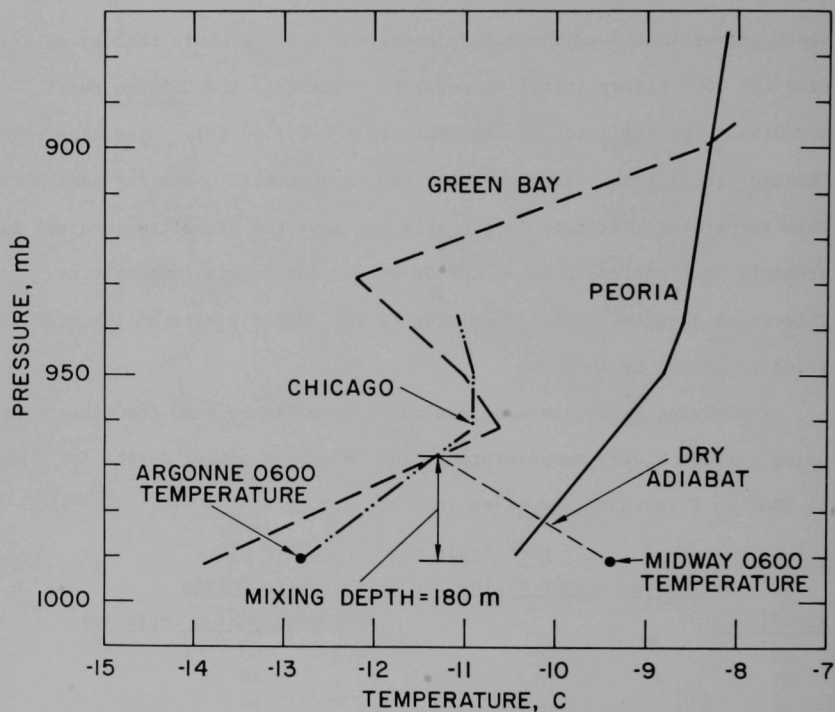
The mixing depth was also estimated from Figure 6.10 for other hours using current Midway temperatures. The estimated mixing depths for 0000 to 0800 on 1 February are given in Table 6.3.

Table 6.3

Estimated Chicago Mixing Depths, 1 February 1966

<u>Time (CST)</u>	<u>Estimated Mixing Depth (m)</u>
00	60
01	60
02	60
03	95
04	60
05	95
06	180
07	255
08	430

\* The mixing depth was read as a pressure from Fig. 6.10 and converted to a height above the surface using the measured Peoria pressure - height relationship.



113-1101

Fig. 6.10 Atmospheric Temperature Soundings, Showing Construction of Chicago Rural Sounding and Estimation of Chicago Mixing Depth

### Incident Control Tests

The following "average" meteorological parameters were selected as inputs to the DAVKERN dispersion simulation which is incorporated in the control model:

Temperature - +15 degrees;  
Wind Speed - 1 and 4 mph;  
Turner Stability - 5;  
Mixing Height - .2 miles;  
Wind Direction - 315 degrees.

The "steady state" buildup of pollution as simulated by DAVKERN is shown in Figure 6.8 for both wind speeds. These results indicate that the use of the DAVKERN coupling coefficients in the control model provides a "realistic" incident for which control programs can be generated, although the validity of the absolute value of the DAVKERN air quality estimates has not been verified.

To illustrate the capability of the control model, four programs were run for this incident as shown in Tables 6.1-2. The six hour period from 4 a.m. to 9 a.m. was chosen for control, because it coincides with the highest pollution levels of the incident. The actual loads and minimum loads (i.e., maximum load shifts) for this six hour period were furnished by CECO. These data are shown in Tables 6.1-2 along with the DAVKERN predicted pollution levels if coal were used to produce these loads. The total thermal input required to satisfy these power demands at the two plants over the six hour incident period is  $2.7 \times 10^6$  therms. Thus, if

a general switchover to gas at each plant was imposed due to this incident, this is the number of therms of gas that would have had to be supplied assuming that gas was available and that all boilers could burn 100% gas. (In fact, not all Fisk and Crawford boilers are equipped for dual fuel use, but this constraint can easily be added to the model.) The success of the control program can be measured against this maximum required gas usage.

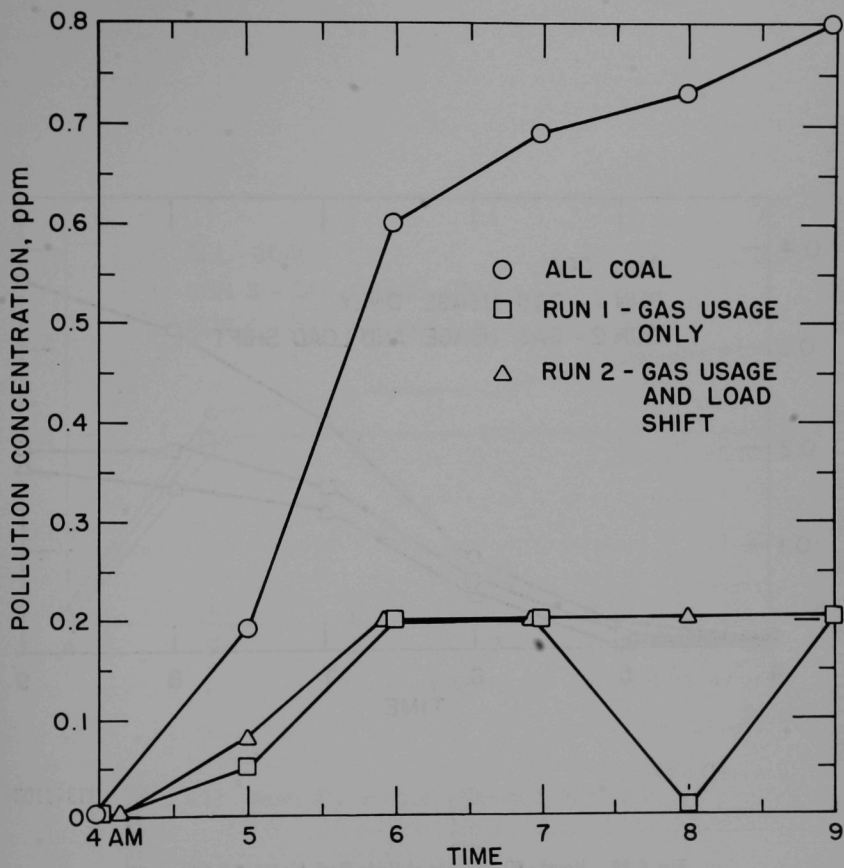
Each program illustrates a different capability of the control model and the savings that can be achieved by its use. These programs are discussed individually below. Figures 6.11 through 6.13 show the hourly  $SO_2$  levels resulting from the use of each program vs. those associated with no control program.

Program #1 - WS = 2 mph, Gas Usage Only

A wind speed of 2 mph was used in runs 1 and 2 because it yields a significant contribution to the Hyde Park station for the 315 degree wind direction. Thus, the entire subsystem linkage is tested. Run 1 assumes that load shifting cannot be imposed and the entire pollution reduction must be achieved by switching to gas. The gas usage program computed by the model and the resulting pollution levels are shown in Table 6.1. The gas usage was  $1.5 \times 10^5$  therms, a reduction of over one order of magnitude.

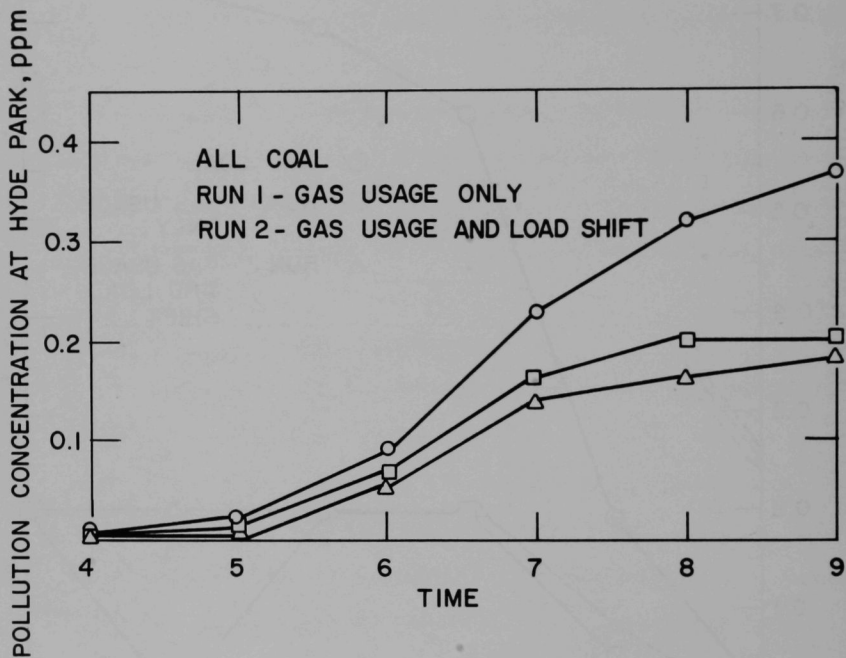
Program #2 - WS = 2 mph, Gas Usage and Load Shifts from Crawford and Fisk

Run 2 is the same as run 1, except now feasible load shifts are allowed. With this program, gas usage at Fisk is no longer needed and the gas input to Crawford is  $4.1 \times 10^4$  therms - another order of magnitude



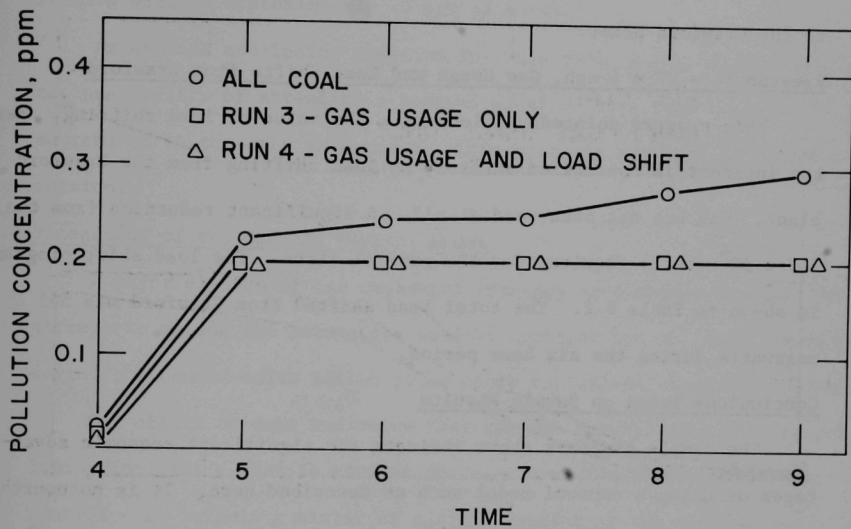
113-1102

Fig. 6.11 Hourly SO<sub>2</sub> Levels at Lindbloom Receptor for Ws = 2 mph



113-1103

Fig. 6.12 Hourly  $\text{SO}_2$  Levels at Hyde Park for  $W_s = 2$  mph



113-1104

Fig. 6.13 Hourly  $\text{SO}_2$  Levels at Lindbloom for  $W_s = 4$  mph

reduction. The total load shifted from the two plants was 1537 megawatts during the six hour period.

#### Program #3 - WS = 4 mph, Gas Usage Only

With a 4 mph wind speed, the contribution to the Hyde Park receptor is no longer significant. This is reflected in the model by no gas usage at the Fisk plant which is the major contributor to Hyde Park for 315 degree winds. This program allocates a total of  $4.6 \times 10^4$  therms of gas to the Crawford plant.

#### Program #4 - WS = 4 mph, Gas Usage and Load Shifts from Crawford

This program pointedly illustrates the value of load shifting. Here the incident is controlled entirely by load shifting from the Crawford plant. Gas has not been used at all. A significant reduction from the  $2.7 \times 10^6$  therms required for the general alarm. The load shift program is shown in Table 6.2. The total load shifted from Crawford was 541 megawatts during the six hour period.

#### Conclusions Based on Sample Results

The sample programs above indicate the significant economic advantages of using a control model such as described here. It is noteworthy that each run took about 6 seconds of 360 model 75 computer time. Thus, control on a near real time basis, through the use of teleprocessing equipment is quite feasible.

It is clear that this control model must rely on the effectiveness of the  $SO_2$  dispersion model. Since the imposition of any control is disruptive, and the amount of control depends on the relative predicted

contributions to pollution levels, one must have assurance that controls are being applied properly and fairly. In other words, if it is indicated that CECO should burn 7200 therms of gas at the Crawford plant between 6 and 7 a.m. to reduce the level of pollution at Lindbloom and Hyde Park to .2 ppm at 9 a.m., control should only be imposed if there is reason for confidence in the prediction that the 9 a.m. air quality reading will be approximately .2 ppm as a result.

An obvious concluding question for this pilot study is to consider the possibility of extending a control model of this type to other  $\text{SO}_2$  sources or to the city as a whole. This topic is explored in the next section.

#### 6.4.7 Extensions of the Optimal Control Model

A major element of our abatement strategy development involves an attempt to extend the automated, optimal incident control model developed during the Commonwealth Edison pilot study to include other  $\text{SO}_2$  sources.

Our effort to date indicates that optimal control of a Chicago pollution incident - that is minimum cost-maximum effectiveness incident control - is largely a matter of optimal control of the natural gas resources available to the City and usable for power production or industrial processing in plants equipped with dual fuel boilers. Other forms of control such as curtailment of industrial operations or control of space heating, are either economically catastrophic or physically unfeasible, excepting through long-range control schemes involving stringent emission control legislation, zoning ordinances, etc.

Fortunately, control of the major power plants are large dual fuel industrial plants would include approximately  $3/4$  of the total  $\text{SO}_2$  emitted in Chicago; hence a significant effect on air quality can be anticipated by imposing short-range optimal controls on these sources.

A major resource allocation problem is associated with the fact that the chief control resource, natural gas, is available in relatively limited quantities during the heating season, when most Chicago pollution episodes occur. It is therefore necessary to allocate this gas to plants where it will have the greatest effect on air quality, and at the same time, to minimize insofar as is possible, the economic impact of enforced use of this rather expensive fuel during the heating season.

We have developed a computerized scheme by which this can be accomplished for the major plants of the Commonwealth Edison power generating network, but we have made no attempt, as yet, to apply this method to the remainder of the dual fuel  $\text{SO}_2$  sources. Additional data must be acquired and an expansion of our optimal control model is necessary. We propose to undertake this effort during the early portion of the second phase of our program; however, the schedule for completion of this task is somewhat dependent on the funding situation that will exist during FY 1969 and 1970.

## .5 Economic Studies

### .5.1 General Discussion

A less sophisticated but more inclusive approach to the evaluation of sulfur dioxide abatement was undertaken concurrently with the "Edison study" described above. The objective of this study was to determine the feasibility and examine the costs involved in the implementation of a city-wide abatement strategy during a general air pollution incident. Since a dispersion model for the complete Chicago area is not yet available, it was necessary to employ sulfur dioxide emission control rather than ambient air quality as the strategy goal.

The conventional separation of sulfur dioxide emitters into utilities, industrial, commercial, and residential sources was adopted, since it allowed the isolation of sources which are administratively unmanageable in the short time periods involved in an incident alert; namely the commercial and residential sources. Except for a few special cases, such sources are too small and numerous to subject to control during an alert.

The first step in conducting the study was to convert the annual  $\text{SO}_2$  emission figures for the four source types into daily figures for the months of October through March when the probability of a major incident is greatest and when most interruptable gas users are using coal and oil. The results are summarized below:

<u>Source</u>	<u>Annual Emissions</u>	<u>Interval When High Sulfur Fuel Is Used</u>	<u>Oct - March Daily Emissions</u>	<u>% of Daily Total</u>
Power Plants	373120 (tons)	8 months	1530 (tons)	62.0
Commercial	47216	6 months	260	10.6
Residential	83027	6 months	457	18.6
Industrial	59138	6 months	107	8.8
		12 months	<u>109</u>	
	<u>562501</u>		2463	<u>100.0</u>

Those industrial plants with known dual fuel capacity are assumed to burn high sulfur fuel during six months of the year (October through March) while all others are assumed to burn it uniformly throughout the year.

Because of the administrative problems described above, the emphasis in the development of an emission-oriented alert system must be placed on control of the utilities with 62% of the daily SO<sub>2</sub> emissions and industry with 8.8%. This implies that almost 30% of all SO<sub>2</sub> emissions are uncontrollable - a percentage which increases during abnormally cold periods, since residential and commercial emissions are highly temperature dependent.

#### 6.5.2 Power Plant SO<sub>2</sub> Abatement

Because their operation was evaluated in some depth as a part of the study outlined in 6.1, the six urban Commonwealth Edison plants are not treated here in as much detail as would otherwise be indicated. Nevertheless, an outline of the economics of CECO abatement strategy

is important in integrating various alternative sulfur dioxide incident control strategies. Three major abatement strategy possibilities are feasible. These are high/low sulfur fuel switching; power load shifting to generating plants outside the Chicago area and the purchase of power from plants outside the CECO system.

#### Load Shifting and Power Purchasing

Since only 38% of the power generated by the total CECO, Northern Illinois and Indiana power system is generated at the six metropolitan Chicago plants, the possibility of significant load shifting is an attractive alternative. Unfortunately transmission line capacity constraints within the CECO system appreciably limit the effectiveness of this technique. Although Commonwealth Edison estimates that 99 days out of 100, it could generate 22% of the electricity produced at the six urban plants outside the metropolitan area (principally by filling in off-peak loads at other plants), the power grid is set up so that only 11% could be transmitted into the city. About 50% of the time, 22% could be shifted, and on exceptional, low demand days, up to 50% could be shifted.

For an air pollution abatement strategy it is prudent to rely only on the relatively certain 11% shift which would yield a 6.8% reduction in total sulfur dioxide emissions in the city (11% of 62.0%) at a cost estimated by CECO of \$2725/day or \$380/day grand percent reduction in SO<sub>2</sub> emissions.

222

The same transmission line constraint makes purchasing power from other systems an impractical option, excepting in cases of extreme emergency, since the CECO system itself has more than sufficient capacity to generate enough power to supply the city and the purchased power is generally more expensive to CECO than is power produced within the system.

#### High/Low Sulfur Fuel Switching

Two possible options for fuel switching exist - switching from coal to gas or from high sulfur coal to low sulfur coal; however, the latter alternative is not technically feasible without significant modification of the CECO boiler system.

All of the CECO plants in the Chicago area, excepting the Northwest plant (which burns less than 3% of the six plant total coal consumption), have the capacity to switch to gas (at least partially) when gas is available. In terms of capacity this ability to shift is broken down below.

<u>Plant</u>	<u>Total Capacity (megawatts)</u>	<u>Capacity Which can be Shifted to Gas (megawatts)</u>
Ridgeland	667	645
Crawford	669	599
Fisk	554	344
Calumet	210	153
State Line	<u>923</u>	<u>385</u>
Total	3023	2126

Thus slightly over 70% of the total capacity of these five plants can be shifted to gas. Since the average utilization of total plant capacity over a normal working day is below 70%, this limitation on the

ability to use gas would seem to be significant only during a few peak hours. A more exact estimate of the limitation is in process but is not yet available; since the effect is apparently slight, it is ignored in the remainder of this study; thus a 100% shift from coal to gas is assumed to be possible for the purposes of the present analysis.

Since the sulfur content of gas is virtually zero (roughly .02 lbs for the gas heating equivalent of a ton of coal), switching to gas would remove a final 53.5 grand percent  $\text{SO}_2$  emission attributable to CECO after a minimum power load shift of 11% had already eliminated 6.8 grand percent of emissions. Thus:

62.0%	CECO Contribution to City $\text{SO}_2$ Emissions During Winter Period
<u>-1.7%</u>	Northwest Unswitchable Capacity
60.3	
<u>-6.8</u>	Grand Percent Removed by Load Shifting
53.5	

To estimate the cost of the gas/coal shift, daily coal consumption figures are required. The six CECO plants burned 6,570,000 tons of coal in 1967 during an eight months period - or an average of 26,600 tons/day. The coal cost slightly under 3¢ a therm with a BTU rating of 10,200 BTU/lb. The CECO air pollution gas contract with Peoples Gas, Light and Coke Co. provides for a small block of winter gas at 7¢ a therm, for a 4¢ therm cost differential. The total daily cost of winter gas shift would thus be approximately:

$$\frac{26,600 \text{ tons}}{\text{day}} \times \frac{204 \text{ therms}}{\text{ton}} \times \frac{4¢}{\text{therm}} = \$217,500/\text{day}.$$

This is equivalent to \$4070/day/1% total  $\text{SO}_2$  reduction. It should be emphasized that only a limited amount of winter gas is available to CECO, and that if the temperature is extremely low, even this gas may be unobtainable. The question of whether any surplus gas available during an air pollution crisis would be most effectively used by CECO or by other  $\text{SO}_2$  emitters is considered below.

Shifting CECO from high sulfur to low sulfur coal would avoid the question of gas availability if it were technically feasible, but this is not the case without substantial equipment modifications. The high ash fusion point of low sulfur coal means that the boiler waste must be extracted as a solid rather than as the liquid that the present CECO boilers are designed to handle. A study of Ohio electric utilities with 4025 megawatts of capacity revealed that conversion costs of \$271 Million would be required. Applying a cost of \$.67 Million/megawatt to CECO's 3400 megawatts of capacity yields a capital cost estimate of \$228 Million to render the CECO boilers capable of using low sulfur coal.

An interesting sidelight of boiler conversion is that reducing the  $\text{SO}_2$  in the effluent degrades the efficiency of the electrostatic precipitators - thus lowering the amount of fly ash removed from the emissions. Improvement of the  $\text{SO}_2$  situation therefore tends to aggravate a related air pollution problem. This effect results from the fact that  $\text{SO}_2$  is a relatively good electrical conductor. The Ohio study estimated that \$33 Million of additional equipment would be required to allow switching to low sulfur coal while maintaining precipitator efficiency.

In any case, high/low sulfur coal switching does not appear to be a workable alternative for CECO, at least in the short run, leaving gas availability as the critical resource in the implementation of a CECO emission control exercise.

### 5.3 Industry SO<sub>2</sub> Emission Abatement

As in the case of the power plant complex, there are two basic methods of reducing industrial sulfur dioxide emissions; reduced activity and substitution of lower sulfur fuels. Unlike the CECO situation, however, the former alternative-rife with economic disruption and adverse competitive effects - does not appear to be a practical recourse at present.

#### Reduced Industrial Activity

Two major costs are involved in the curtailment of industrial processing activity, the direct and indirect value of foregone production and damage to capital. In this situation, order of magnitude figures for wage losses alone indicate that temporarily halting industrial operators is not a viable alternative. Using 1967 Chicago manufacturing data, the wage losses if all major industrial operations were curtailed for one day would be over \$12 Million, as indicated below:

$$\frac{\$3.14}{\text{man-hour}} \times 8 \text{ hours} \times 480,000 \text{ workers} = \$12,050,000.$$

Whether workers are laid off or are paid for not working is unimportant and only determines whether the employer or employee bears the loss. The cost per grand percent of SO<sub>2</sub> emission is over a million dollars -

on the basis of one-shift working day,

$$\frac{\$12,050,000}{8.8\%} = \$1,370,000/\text{grand percent reduction in SO}_2 \text{ emission.}$$

Some of this wage loss would no doubt later be recovered through overtime, but other losses such as reduced profits, capital damage (blast furnace linings, limestone kiln walls, spoiled food processing inventories, etc), and any indirect effects have been ignored. Indirect effects include any "multiplier effects" of losses - the reduced income to those who would normally sell to those who have suffered losses. In view of this situation, the only practical recourse for economically feasible industrial emission control lies with low sulfur fuel substitution.

#### High/Low Sulfur Fuel Switching

The ninety-nine largest industrial sulfur dioxide emitters represent a wide assortment of coal, oil, and gas users; some are switchable to lower sulfur fuel, some are not. A summary of total emissions from the various boiler types appears below:

<u>Type of Boiler</u>	<u>Annual Tons of SO<sub>2</sub></u>	<u>Tons of SO<sub>2</sub> per day Oct - March</u>
Coal-gas convertible	14779	81.2 (37.8%)
can use low sulfur coal	7487	
cannot use low sulfur coal	7292	
Coal only	21349	58.5 (27.2%)
can use low sulfur coal	6758	
cannot use low sulfur coal	14591	
Oil-gas convertible	4680	25.6 (11.8%)
Oil only	<u>6847</u>	18.7 (8.6%)
Total for 99	47655	
Plants other than 99	<u>11483</u>	<u>31.5</u> (14.6%)
Total Industrial	59138	215.5 (100%)

From the table it is clear that 49.6% of the 8.8% winter-month industrial grand percent could be eliminated by switching to gas if available; 37.8% by coal/gas switching and 11.8% by oil/gas switching. It is important to separate these two methods, since the cost effectiveness of each is different.

The analysis of the shift from coal to gas follows the pattern of the power plants. The price of coal to the lower volume industrial users is slightly higher - roughly 3.1¢ a therm (for Southern Illinois coal costing \$6.78 a ton and of 11000 BTU/lb). The price of gas is uncertain, since none of the 99 industrial users have bargained with the gas supply utility for wintertime air pollution gas as has CECO. Peoples Gas, Light and Coke Co. has an emergency rate of 12¢ a therm which would seem to be applicable, but for the sake of cost-efficiency comparisons with CECO, the 7¢ therm price that CECO received was applied to the industrial analysis.

The incremental cost of substituting gas for coal is \$16,300/day as shown below:

$$\frac{(7¢ - 3.1¢)}{\text{therm}} \times \frac{1896 \text{ tons coal}}{\text{day}} \times \frac{220 \text{ therms}}{\text{ton}} = \$16,300/\text{day}.$$

The cost per grand percentage of industrial SO<sub>2</sub> emission reduction is therefore:

$$\frac{\$16,300}{37.8\% \text{ of } 8.8\%} = \frac{\$16,300}{3.3\%} = \$4940/\text{grand percent}.$$

This estimate applies up to a maximum of 3.3 grand percent.

The incremental cost of substituting gas for oil can be found by a similar method. The price per therm of #6 oil is 4.9¢ a therm (calculated from a price of \$.075 per gallon and a BRU rating of 151,000 BTU per gallon). The daily cost of oil-gas switching then is \$5420, as shown below:

$$\frac{(7¢ - 4.9¢)}{\text{therm}} \times \frac{172,000 \text{ gallons oil}}{\text{day}} \times \frac{1.5 \text{ therms}}{\text{gallon}} = \$5420/\text{day}.$$

The cost per grand percent reduction is thus:

$$\frac{\$5420}{11.8\% \text{ of } 8.8\%} = \frac{\$5420}{1.04\%} = \$5200/\text{grand percent}.$$

This applies up to a maximum of 1.04 grand percent.

Of the non-switchable (coal-only) boilers, those responsible for approximately 6758 tons per year of SO<sub>2</sub> emission (32% of the coal-only boiler emissions) or 18.5 tons per day have burners which can efficiently accommodate low sulfur coal. Traveling grate stokers, the major part of the remaining 68%, require coal with a large ash content but low caking properties - a combination of characteristics found only in the higher sulfur coals. The other 32% can be shifted to low sulfur coal, though not without some loss of efficiency.

To analyze the economics of a high/low sulfur coal shift, we have the following characteristics:

<u>Coal Source</u>	<u>Avg. Sulfur Content</u>	<u>Mine Price per Ton</u>	<u>Transport Cost in 2500 Ton Lots</u>	<u>Total Delivered Price</u>
Southern Illinois	3.3	\$3.85	\$2.93	\$6.78
Western Kentucky	3.45	3.45	3.40	6.85
Eastern Kentucky	1.00	4.27	5.12	9.39

The Southern Illinois and Western Kentucky coals average 11000 BTU/lb while Eastern Kentucky coal averages 13000 BTU/lb. This energy difference narrows the differential cost of using premium, Eastern Kentucky coal to \$2.20/ton.

On the average day, the coal-only boilers which allow switching to low sulfur coal burn 368 tons of high sulfur coal. The cost of switching to low sulfur coal then is,

$$\frac{368 \text{ tons}}{\text{days}} \times \frac{2.20}{\text{ton}} = \$810/\text{day}.$$

Since this could be expected to reduce the daily SO<sub>2</sub> emissions from 18.5 tons/day to 5 tons/day or by 13.5 tons, the cost per grand percent reduction is,

$$\frac{\$810}{.55 \text{ grand percent}} = \$1470/\text{grand percent per day}.$$

up to a maximum of .55 grand percent.

The following information is useful in determining the cost and effect of high/low sulfur oil switching.

<u>Type of Oil</u>	<u>Avg. Sulfur Content</u>	<u>Price per Gallon 6000 Gallon Lots</u>	<u>BTU per Gallon</u>
#2	.4	\$.110	142,000
#6	2.5	\$.075	151,000

In general then, for an incremental cost of \$.037 per gallon for using #2 oil in place of #6, we could expect a 79% reduction in sulfur dioxide emissions. However, a weight average of the sulfur content of #6 oil in oil-only boilers as indicated in the emission inventory, turns out to be

.9% - not near the 2.5% general average, - so the SO<sub>2</sub> reduction achieved is only 51% for shifting to #2 oil or 9.35 tons.

The total cost would be:

$$\frac{254,000 \text{ gallons}}{\text{day}} \times \frac{\$.037}{\text{gallon}} = \$9400/\text{day},$$

which, per grand percent, is

$$\frac{\$9400}{.38\%} = \$24800/\text{grand percent}/\text{day}.$$

This cost is much higher than for coal, partially because of the low initial sulfur content and partially because of the large proportional increase of #2 oil price over #6.

Assuming that gas is available, the total strategy alternatives are presented below in tabular form from least to most costly per grand percent SO<sub>2</sub> emission reduction.

<u>Method</u>	<u>Percent Reduction in Industrial Emissions</u>	<u>Grand Percent Reduction</u>	<u>Cost per Grand Percent</u>	<u>Total Cost</u>
High/Low S. Coal	6.3	.55	\$ 1470	\$ 810
Coal/Gas	37.8	3.30	4940	16300
Oil/Gas	11.8	1.04	5200	5420
High/Low S. Oil	<u>4.3</u>	<u>.38</u>	24800	<u>9400</u>
	60.0	5.27		\$31930

If gas were not available, the situation would change considerably. Examination of emission inventory data reveals that only 41.2 tons of the 81.2 tons of SO<sub>2</sub> emitted by coal/gas boilers were produced by boilers with stokers which allow the use of low sulfur coal. The others must remain uncontrolled. The substitution of Eastern Kentucky coal

would eliminate only about 20 tons of  $\text{SO}_2$ , since the weighted average sulfur content of coal in this category is less than 2%. Since we have already calculated the cost of the high/low sulfur coal switch, we need only apply it to the twenty ton reduction. The total cost of eliminating this  $\text{SO}_2$  tonnage is,

$$\frac{20}{215.5} \times 8.8 \text{ Grand Percent} \times \frac{\$1470}{\text{Grand Percent}} = \$1204.$$

The oil/gas boilers could also be switched to low sulfur oil, if gas were unobtainable. Because the weighted average sulfur content of the #6 fuel oil used in these burners (as indicated in the emission inventory) was 1.9%, switching to low sulfur oil would be a more effective measure in this case than in the situation involving oil-only boilers. Seventy-four percent of the daily 25.6 tons of  $\text{SO}_2$  would be eliminated by switching to #2 oil or 0.784 grand percent. The cost of the switch would be,

$$\frac{171,000 \text{ gallons oil}}{\text{day}} \times \frac{\$.037}{\text{gallon}} = \$6350/\text{day}.$$

This works out to \$8100/one grand percent reduction in  $\text{SO}_2$ .

$$\frac{\$6350/\text{day}}{0.784 \text{ grand percent}} = \$8100/\text{grand percent}/\text{day}.$$

The effectiveness of the total abatement strategy if gas is not available, is thus less impressive than when gas can be used. The relevant figures are shown below:

<u>Method</u>	<u>% Reduction in Industrial Emissions</u>	<u>Grand Percent Reduction</u>	<u>Cost per Grand Percent</u>	<u>Total Cost</u>
High/Low S. Coal	6.3	.55	1470	810
	9.3	.82	1470	1204
High/Low S. Oil	4.3	.38	24800	9400
	<u>8.8</u>	<u>.78</u>	8100	<u>6350</u>
	28.7	2.53		17,764

These results indicate that the possible reduction in SO<sub>2</sub> emissions from industry is more than halved when gas is not available.

#### Power Plant - Industry Abatement Strategy Summary

The total abatement options available to the city of Chicago are summarized below with gas available:

<u>Method</u>	<u>Grand Percent SO<sub>2</sub> Emission Reduction</u>	<u>Cost/Grand Percent/day</u>	<u>Cost/day</u>
CECO Power Shift	6.8	\$ 380	\$ 2750
Industry H/L Sulfur Coal	.55	1470	810
CECO Coal/gas	53.5	4070	217500
Industry Coal/gas	3.30	5200	16300
Industry Oil/gas	1.04	24800	5400
Industry H/L Sulfur Oil	<u>.38</u>		<u>9400</u>
	65.57		\$252,160

When gas is available, then, a sulfur dioxide alert system appears to be an effective, if expensive, method of dealing with an incident at least relative to gross average emissions. For \$250,000/day, almost sixty-six percent of all city SO<sub>2</sub> emissions could be eliminated, however, with no gas available:

<u>Method</u>	<u>Grand Percent SO<sub>2</sub> Emission Reduction</u>	<u>Cost/Grand Percent/day</u>	<u>Cost/day</u>
CECO Power Shift	6.8	\$ 380	\$ 2750
Industry H/L Sulfur Coal	1.4	1470	2014
Industry H/L Sulfur Oil	.8	8100	6350
	<u>.4</u>	24800	<u>9400</u>
	9.4		\$20,514

If an incident should occur when large quantities of natural gas were not available, all alternative control strategies would be largely ineffective, and less than ten percent of city-wide sulfur dioxide emissions could be eliminated. To the degree that gas is available, this analysis indicates that it should be allocated to CECO and to industrial plants with boilers which do not allow switching to low sulfur coal; namely those equipped with traveling grate stokers.

The availability and optimum allocation of natural gas remain two of the most important problems not yet resolved. One of the next stages of this study will be to attempt to deduce the form of the relationship between gas availability and ambient temperature by studying the quantities of gas made available to interruptable gas customers at different temperatures, times and seasons. A cursory examination of gas utilization data reveals that, below 35°F, there is little likelihood of any gas being available for air pollution control purposes.

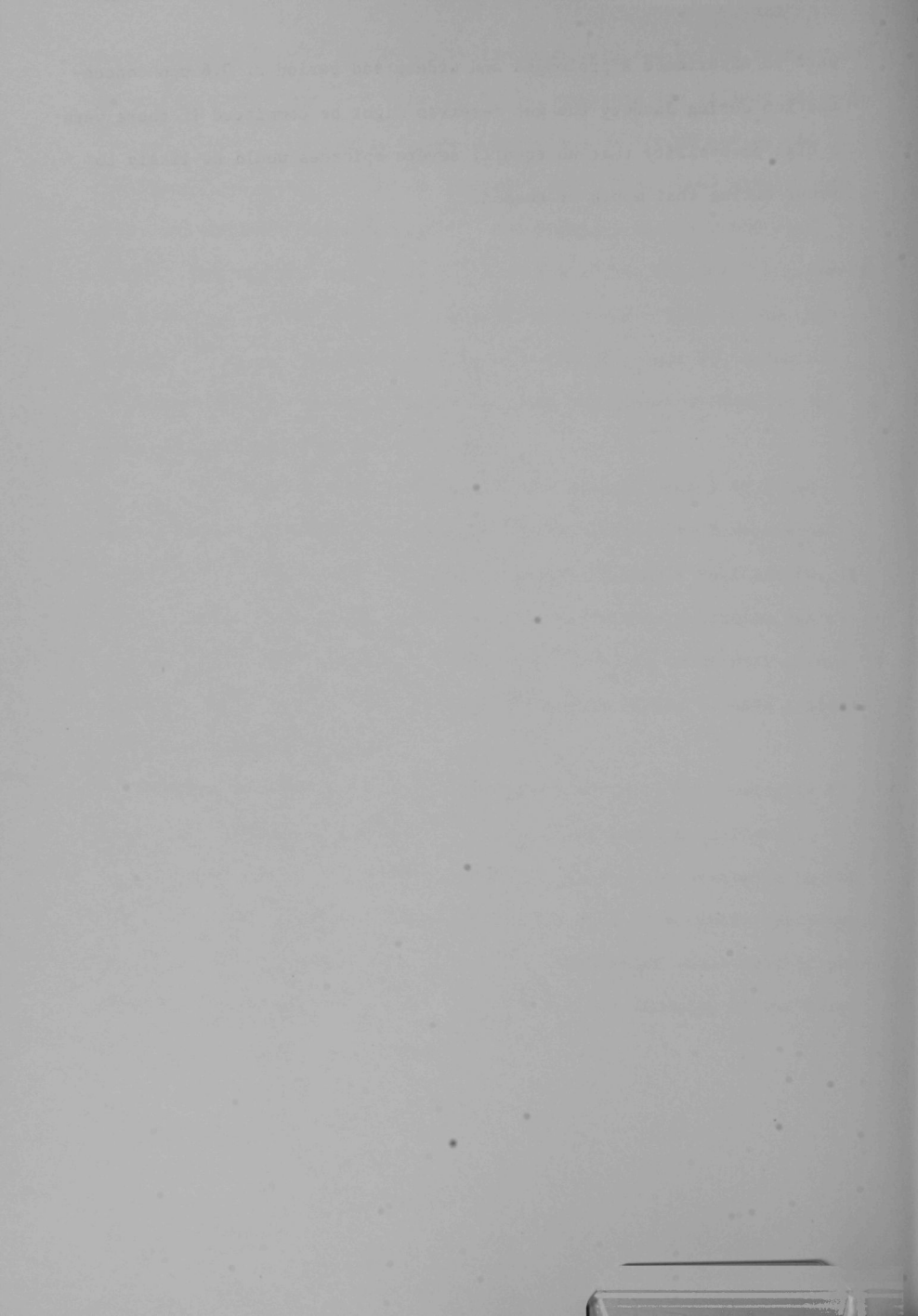
The development of a sophisticated optimal gas allocation strategy awaits the development of city-wide SO<sub>2</sub> dispersion model. When that model is operational, a mathematical program comparable to that

described in 6.1, with an objective function weighted by the population density in each local area affected by  $\text{SO}_2$  emitters (to reflect the benefits of cleaner air), and with the available quantity of gas as one of the imposed constraints, can be created. Until then, some simple wind direction analogue might be useful. For example, if the winds were largely from the West or North,  $\text{SO}_2$  emitters in the Calumet area, itself not densely populated, might be ignored completely. This is the case because that area, though responsible for 22% of annual  $\text{SO}_2$  emissions, in Chicago would contribute little to local  $\text{SO}_2$  concentrations in the major population centers of the city.

An effective  $\text{SO}_2$  dispersion model will also be useful in determining whether available gas should go to industry or to Commonwealth Edison. It may in fact develop that, because of CECO's tall stacks, it would be most effective if CECO never used its winter pollution gas reserve. This reserve could then be made available to industrial plants equipped with shorter stacks which would be more likely to have a significant impact on air quality.

An additional aspect of  $\text{SO}_2$  abatement that is to be considered is associated with the probability of repetitive pollution incidents. Assuming that there is a certain amount of reserve gas available to the city during the course of the winter for air pollution control purposes, it is feasible to develop a probabilistic model which would make it possible to decide when to expend the reserves. For example, if the city

were to experience a prolonged and widespread period of 0.6 ppm concentration during January the gas reserves might be committed if there were a high probability that no equally severe episodes would be likely to recur during that month or season.



## CHICAGO AIR POLLUTION DISPERSION MODEL

### 7.0 Air Pollution Operations Manual

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## 7.0 Air Pollution Operations Manual

On July 1, a twelve-month effort to develop an air pollution control operations manual was initiated as an adjunct to the mainstream system analysis program. The objective of this peripheral effort was to consolidate, in manual form, a set of guidelines for the establishment of an urban SO<sub>2</sub> air pollution control program. Two significant criteria were imposed on the development of this manual:

1. It must be designed for use at least in the fifty largest cities in the United States; that is, the utility of the manual must not be predicated on the possession of the extensive facilities, large staff and budget that are normally associated with air pollution control operations in a megalopolis such as Chicago, New York or Los Angeles.
2. It must be designed for direct use by air pollution control administrators and engineers rather than for the benefit of scientific personnel. Thus, the manual could not be a straightforward summary of progress in the technical aspects of air pollution control. The administrative structure required for the conduct of an air pollution control operation is relevant for the manual, and the proposed general approach to air pollution control must be as pragmatic as possible.

To accomplish this, four major task areas have been identified:

1. Development of a standardized technique for the accumulation of an approximate SO<sub>2</sub> emission inventory of sufficient accuracy to permit the formulation of practical incident control contingency plans.

2. Development of approximation techniques for the assessment of the air pollution potential of an urban area.
3. The development of a simplified technique for predicting ambient  $\text{SO}_2$  concentrations with sufficient accuracy to permit the implementation of abatement strategies.
4. The development of a matrix of limited, practical  $\text{SO}_2$  abatement strategies which could be implemented within the constraints imposed by the air pollution control resources of a city of moderate size.

To a considerable extent, the preparation of the operations manual involves the evaluation, interpretation and codification of methodologies, procedures and organizational techniques developed in the recent past by and for the National Air Pollution Control Administration (NAPCA) and other agencies. To undertake, as part of a short-term, limited budget effort, a program of research designed to achieve significant state-of-the-art advances beyond what has been accomplished in the recent past throughout a broad spectrum of ESSA and NAPCA studies, municipal air pollution control programs, etc. would be impractical. On the other hand, the consolidation of existing methodologies for the development of emission inventories, pollution forecasting techniques and abatement strategies, including those developed for the City of Chicago program, is quite feasible.

Although much of the effort to assemble the operations manual must be more interpretive than innovative, two of the task areas described above involve limited applied research studies which will be conducted in parallel with and with support of the mainstream system analysis

program. These are the development of a set of practical SO<sub>2</sub> abatement strategies and the development of an approximate, receptor oriented, SO<sub>2</sub> incident prediction methodology.

#### 7.1 Air Pollution Abatement Planning

The development of practical SO<sub>2</sub> incident abatement strategies is a task that is complicated by the organizational difficulties of administering an incident control exercise, the diversity of sources that might be subject to emission control, the operational and economic penalties involved in the imposition of temporary controls on certain types of sources and the effective impossibility of controlling other SO<sub>2</sub> sources such as space heating plants. By contrast, the task of long-range air pollution control planning, which is accomplished through the enactment of emission control laws, zoning ordinances, etc., is considerably less difficult.

The problem in developing incident control strategies - assuming that an adequate source inventory is available - devolves to five basic elements:

1. The ability to either forecast the advent of an incident or to monitor on a near-real time basis, the air quality of the threatened area. The latter element is an absolute minimum requirement, since at the very least, it is necessary to know that an incident has begun in order to initiate a control exercise.
2. An understanding of the operating cycle, spatial distribution and degree of controllability of those SO<sub>2</sub> sources that are subject to control.

3. A means of estimating the relative effectiveness of controlling a given source or aggregate of sources in terms of the probable resultant improvement in air quality.
4. A command and control structure through which a control plan can be implemented. That is, the administrative mechanism for implementing and enforcing a control plan must exist and be in operational readiness.
5. A set of contingency control plans.

The assemblage of these five elements does not imply the development of optimal control plans, or even of maximum effectiveness control plans, but these are the essential components of what might best be termed practical abatement strategies. The development and/or codification of methodologies for providing these elements in a moderate to large sized city is the objective of the incident control strategy development effort.

## 2 Air Pollution Prediction

Past attempts to develop air pollution prediction systems have largely been oriented around the construction of air pollution dispersion models based on a more or less complete source inventory and a set of deterministic or empirical dispersion equations designed to assess the transport of pollutants from source to receptor. Some of these models, such as those of Turner<sup>(3)</sup>, Koogler<sup>(19)</sup>, Davidson<sup>(20)</sup> or Miller<sup>(21)</sup> have been source-oriented in the sense that the model seeks to trace and aggregate the contributions due to each pollution source included in the system. Other models, such as that of Clarke<sup>(22)</sup>, are receptor-oriented in the sense that they seek to evaluate, at a selected point,

the contributions to the ambient pollutant concentration of all upwind sources that would be expected to affect that point.

These models have in common the fact that none have yet demonstrated sufficient predictive skill to permit their use in the implementation of episode control plans, where forecast accuracy and reliability are essential because of the economic and operational disruptions associated with temporary emission control.

If a dispersion model of the kind hitherto proposed were to be refined to the point that it would yield predictions of sufficient accuracy to allow implementation of pollution incident control plans, the problem of supplying an accurate and current source inventory for the model would remain. It is almost axiomatic that a dispersion model, whether source or receptor oriented, which requires an assessment of source strength and distribution, cannot yield forecasts that are more accurate than the source inventory itself. Unfortunately, the accuracy of a source inventory tends to diminish rapidly with the time span over which emissions are averaged. An annual emission inventory of the kind currently being compiled for the "AIRCENS 67" program in Chicago can be accurate to within about  $\pm 10\%$ , but a daily or hourly inventory can be in error by a factor of at least two or three, depending on the type of source. These large errors are almost unavoidable in a short time horizon inventory, and are due primarily to the fact that only public utilities and the largest industrial plants tend to retain adequate records of fuel consumption. Significant errors are possible even in the development of historical emission data for the extremely well documented

operations of a public utility, since the sulfur content of coal or fuel oil regularly varies by more than  $\pm 15\%$  about a mean value.

Plants equipped for dual fuel operation tend to complicate the inventory problem as well, since these may switch from high sulfur fuel to gas and back sporadically and intermittently during the inventory period.

The task of developing an accurate emission inventory for a medium-to-large city is therefore a complicated one, and it is not surprising that rather gross approximations have been adopted in the development of inventories for many of the dispersion models constructed in the past. For example, the source inventory devised for the Clarke model was based on the assumption that the emission rate of industrial plants was essentially constant - a major, (and defensible) departure from reality, since the Chicago hourly emission inventory has supplied ample evidence that the emission rates of typical industrial processing plants may regularly (or irregularly) vary by at least 100% during a given 24-hour period. It may be argued that errors in an emission inventory will tend to cancel, on the average, in view of the fact that any given source is likely to contribute only a small fraction to the total ambient  $\text{SO}_2$  detected at a point. The difficulty here is that, in a model that is based on the summation of sources, such errors may also compound and result in very significant errors in the predicted air quality. If errors due to an inadequate simulation of meteorological phenomena are superimposed on such source inventory errors, the performance of many of the prediction schemes devised in the past may readily be explained.

If it is assumed that a perfect source inventory could be developed for a time horizon - say 24 hours - that is reasonable for incident control, it is still necessary to consider the problem of maintaining the currency of this inventory. The development of an annual inventory for Chicago, using the resources, manpower and computer facilities of one of the best endowed air pollution control departments in the United States, requires a minimum of 12-18 months. During this interval, building, demolition, the constantly varying urban land use patterns of a major city and the increasing implementation of air pollution control laws which tend to discourage the use of high sulfur content fuels tend to render the source inventory obsolescent. Updating and adjustments can be made to compensate for the effects of urban evolution, but the magnitude of the error involved is not easily assessed.

The significant point here is that it has not yet been demonstrated that an emission inventory that is adequate for use in a real-time, source-sensitive, air pollution incident prediction model can be developed and maintained - even if the resources of a major city are available for the task. It is important to note here, however, that an emission inventory is an essential component of an air pollution control operation, whether or not it is possible to base an effective dispersion model on such data. This is the case because a knowledge of the magnitude, distribution and normal operating cycle of controllable pollution sources must be available in order to formulate practical contingency control plans and to support routine enforcement activities.

It is, of course, possible to "sensitize" a dispersion model to source distributions without having a rigorously accurate or up-to-date source inventory - the Clarke and Miller models are cases in point. To minimize overprediction and obtain reasonably good "skill scores" with the Clarke area source-sensitive model, however, Schiermeyer<sup>(23)</sup> reports that it was necessary to eliminate all residential space heating emissions from the source inventory - a reasonable, empirical adjustment of the model. Similar empirical adjustments are required for the Miller model, however, the necessity for imposing such modifications raises a question concerning whether this type of model is then actually source sensitized. The emission inventory might simply be regarded as a convenient but arbitrary device for tailoring the model to the receptor used in its validation. It is not clear that a model so adjusted may still be regarded as a purely source-oriented prediction scheme.

The considerations discussed above, that is:

1. The difficulty and magnitude of the task of developing and maintaining an accurate, real-time, short time-horizon, emission inventory.
2. The questionable value, for a predictive diffusion model, of an "approximate" emission inventory led to the proposition that a totally receptor-oriented air pollution incident prediction scheme might prove to be the most practical approach for operational air pollution incident control in medium-sized cities.

In this context, a totally receptor oriented prediction scheme would be based on the statistical correlation of historical air quality and

meteorological data for the city in question. Such a "model" can be source-sensitized to a considerable extent by the development of sets of prediction algorithms corresponding to each wind sector, time period and season. Since the data necessary to construct such a prediction system can be accumulated and stored automatically, the manpower resources necessary to develop and maintain a detailed source inventory are not required - moreover such a system can be sensitized to the urban evolutionary cycle by periodic, and essentially automatic, updating with recent meteorology and air quality data.

In order to develop such a system, it is evident that an inventory of recent (not more than about one year old) air quality and meteorology data must be available for each subject city. The latter would appear to pose no serious problem, since U. S. Weather Bureau records are routinely stored in standard computer format at the Asheville, N. C. Weather Records Center. On the other hand, a network of air quality monitoring stations comparable to Chicago's is not yet available in most cities. Many major cities possess CAMP stations, or will be equipped with comparable air quality monitoring equipment under projected NAPCA programs.

It is worth noting here that the number of monitoring stations available in a city cannot be used as reliable indicator of the utility of a receptor oriented prediction model which depends, for its creation, on the availability of local air quality data. It may be argued that a perfect source-oriented model could be validated with data from a

single monitoring station and then used to predict pollution concentrations at all points in an urban area, but it is not at all clear that such a validation would be justified in a city which was characterized, as most cities are, by a complex aggregate of diverse and widely distributed sources. For the purposes of the present program, it is assumed that at least one, strategically sited monitoring station will be available in each subject city.

To develop a receptor-oriented, source-sensitized, empirical prediction system based on statistical analyses of meteorological and air quality data obtained for the subject city, we have elected to employ multivariate discriminant analysis. This technique was described in ANL/ES-CC-002 and in the present report, and is currently being utilized as an analytical tool for the identification of air pollution meteorological regimes under the auspices of the mainstream system analyses program. Future quarterly reports will discuss the effectiveness of this technique as adapted to the development of a three to five  $\text{SO}_2$  band prediction scheme. It is important to note that the manual development effort is not irrevocably committed to this approach to incident prediction, rather a number of alternative prediction models are being considered for inclusion in the prototype manual.

### 3 Progress Achieved to Date

During the first quarter of this program, the following tasks were undertaken:

1. A fairly sophisticated multivariate discriminant analysis computer code which provides the capability of automatically rejecting

parameters which are not significant discriminant variables was acquired, modified and adapted for use on the Argonne IBM 360-75 computer. This code has been tested and is now being incorporated into the master information system.

2. The development of a computer algorithm for estimating hourly variations in the urban mixing layer depth was initiated. This algorithm is now near completion, and will be used for both the system analysis program and the manual study.
3. A Calcomp plotting computer routine was developed and adapted for use with the master information system. This algorithm generates parallel time series plots of TAM air quality and selected meteorological parameters. These automated plots serve to facilitate air pollution incident analyses for both the mainstream system analysis program and the manual development study.
4. An organizational study of the Chicago Department of Air Pollution Control was initiated in order to identify administrative techniques, policies and procedures that can be adapted to the situation of cities of smaller size than Chicago.
5. A Chicago consulting meteorology firm was retained to prepare a historical log of estimated, hourly mixing layer depths for the period July 1, 1968 to July 1, 1969.

The same firm will assist Argonne in the preparation of an organizational design for a model air pollution meteorology forecasting operation. This model organization, if properly developed, can be used either

as a guide to municipal air pollution control agencies which seek to establish their own in-house forecasting capability or as a device to assist those which seek to retain a commercial forecasting firm on a contract basis in the determination of what services and capability are required. In either case, the model organization will be tailored to mesh with the evolution of the national air pollution alert system and current, related NAPCA studies and will be based on the need for local, micrometeorological air pollution forecasts to supplement the large-scale, airshed-level forecasts which will be supplied under the national alert system.

#### 4 Conclusions

It is reasonable to consider the question of whether the state-of-the-art of air pollution control is sufficiently advanced, as yet, to warrant the development of a document such as the proposed "operations manual." If a city as well endowed as Chicago is not yet in a position to implement incident control strategies, it is feasible to question the propriety of an attempt to codify procedures for such activity in lesser municipalities. It is our position that the development of an operations manual must, at best, be an iterative process in which successive modification and updating of a prototype document will eventually result in the kind of engineering and administrative guide to air pollution control that must ultimately be supplied by NAPCA. We therefore regard the development of a prototype manual, whether it be regarded as a first or second generation effort, as an appropriate and necessary

undertaking at this stage of the national air pollution control program, and we believe that the current state-of-the-art of air pollution control warrants the initiation of such an effort.

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